Magnetic Resonance Atlas of Skeletal Development of the Knee

A Standard of Reference

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History of Bone Age Assessment

Proper assessment of skeletal development is essential for managing many conditions of bone and joints. Interest in this topic began nearly 100 years ago by T. Wingate Todd a Professor of Anatomy at Western Reserve University. In 1926 a series of studies in Cleveland, OH were initiated with a goal of creating radiographic standards of reference for skeletal maturation based on the hand, elbow, shoulder, hip, knee, and foot. Between 1931 and 1937, tentative developmental standards were assembled for each of these joints. Unfortunately, with the untimely death of Professor Todd, most of these series were never completed. Fortunately, William Walter Greulich and S. Idell Pyle carried on the work of Professor Todd and published the *Radiographic Atlas of Skeletal Development of the Hand and Wrist* in 1950. Since its publication, this reference has become the "gold standard" for assessing bone age and it is widely used across multiple sub-specialties including endocrinology, pediatrics, and orthopedics.

Drawbacks of the Greulich and Pyle Atlas

While widely used, there are limitations and drawbacks to the Greulich and Pyle Atlas:

1. It is based on a single left hand radiograph and the maturation of other joints (such as the knee) have been shown to be independent of the hand.
2. The original "source films" came from "carefully selected" patients from Cleveland, OH which were largely Caucasian with higher socioeconomic backgrounds. This selection bias has potentially limited the applicability of this data to larger and more diverse patient populations seen across many urban areas in the United States.
3. The "source data" is nearing 100 years old and it is unclear whether these standards still apply to children that are now entering puberty at an earlier age.
4. Obtaining an additional left hand radiograph exposes patients to additional ionizing radiation, adds additional cost to the health care system, and potentially slows clinic efficiency.

Alternative Knee Atlas

In 1969, S. Idell Pyle and Normand L. Hoerr published a separate reference entitled *Radiographic Atlas of Skeletal Development of the Knee*. This atlas was created using an identical methodology as the Greulich and Pyle Atlas from knee radiographs that were performed between 1928 and 1942. Interestingly, this atlas is rarely referenced and has not been routinely used in the bone age assessment of patients with knee specific conditions. The reason for this in unclear, but possibilities include (1) the fact that subtle differences between certain age standards (especially in adolescence) can be subtle and difficult to reproducibly identify, (2) compared to the hand and wrist where there are many bones and growth plates, there are less distinguishing radiographic features about the knee to help differentiate certain ages, (3) unlike the Greulich and Pyle Atlas, the knee atlas combines the male and female standards.

Bone Age using Magnetic Resonance Imaging

To date, several studies within the forensic literature have evaluated the utility of knee MRIs for assessing chronological age. The rationale for these studies has been to develop better tools for assessing an accurate age of asylum seekers and resolving immigration proceedings (particularly in Europe). As such, these studies have almost exclusively focused on the ages of 14 to 30 years, as legal responsibility applies to individuals between the ages of 14 and 22 years in most countries. Therefore, the existing forensic literature is largely inadequate for conditions that require an accurate MRI bone age for patients under the age of 14 years.

Purpose of the Current Atlas

The aim of this project was to create a new atlas of knee MRIs across a spectrum of pediatric ages that would be comprehensive enough to discriminate patient bone age during the critical pre-adolescent and adolescent years of 11 to 18 as well as to adequately cover the earlier period from 2 to 10 years.

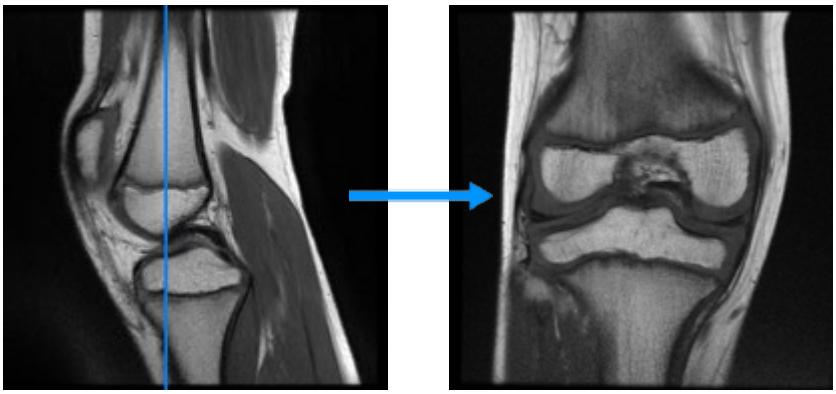
Atlas Creation

Selection of Skeletal Maturity Indicators

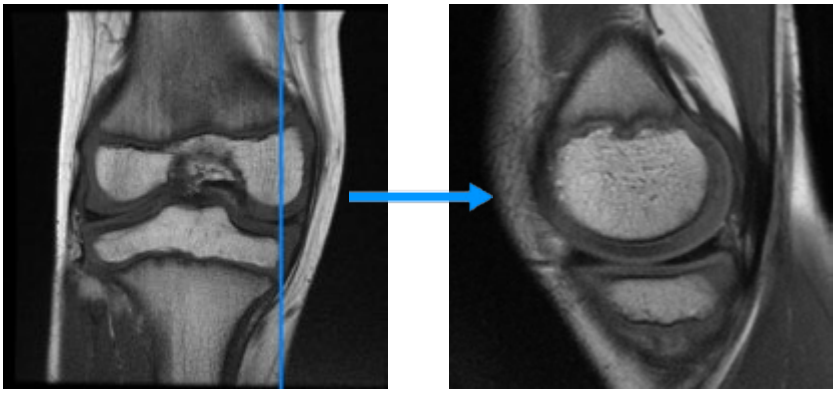
- The knee MRI atlas was created in a similar fashion as the Greulich and Pyle Hand Atlas and the Pyle and Hoerr Knee Atlas.
- First, a preliminary series of skeletal maturity indicators were identified by examining knee MRIs across of a spectrum of skeletal maturity.
- In reviewing hundreds of MRIs, several indicators were identified and independently evaluated for each bone (femur, tibia, patella, and fibula).
- These features were found to be most identifiable and reproducible on the coronal T1 and sagittal T1 images.
- For each bone, a single standardized coronal and sagittal slice was identified.
- A 1.5 Tesla magnet was utilized for all MRIs in this series

Femur Slice Standardization

The coronal slice through the center of the distal aspect of the femur at the attachment site of the posterior cruciate ligament on the medial femoral condyle was selected.

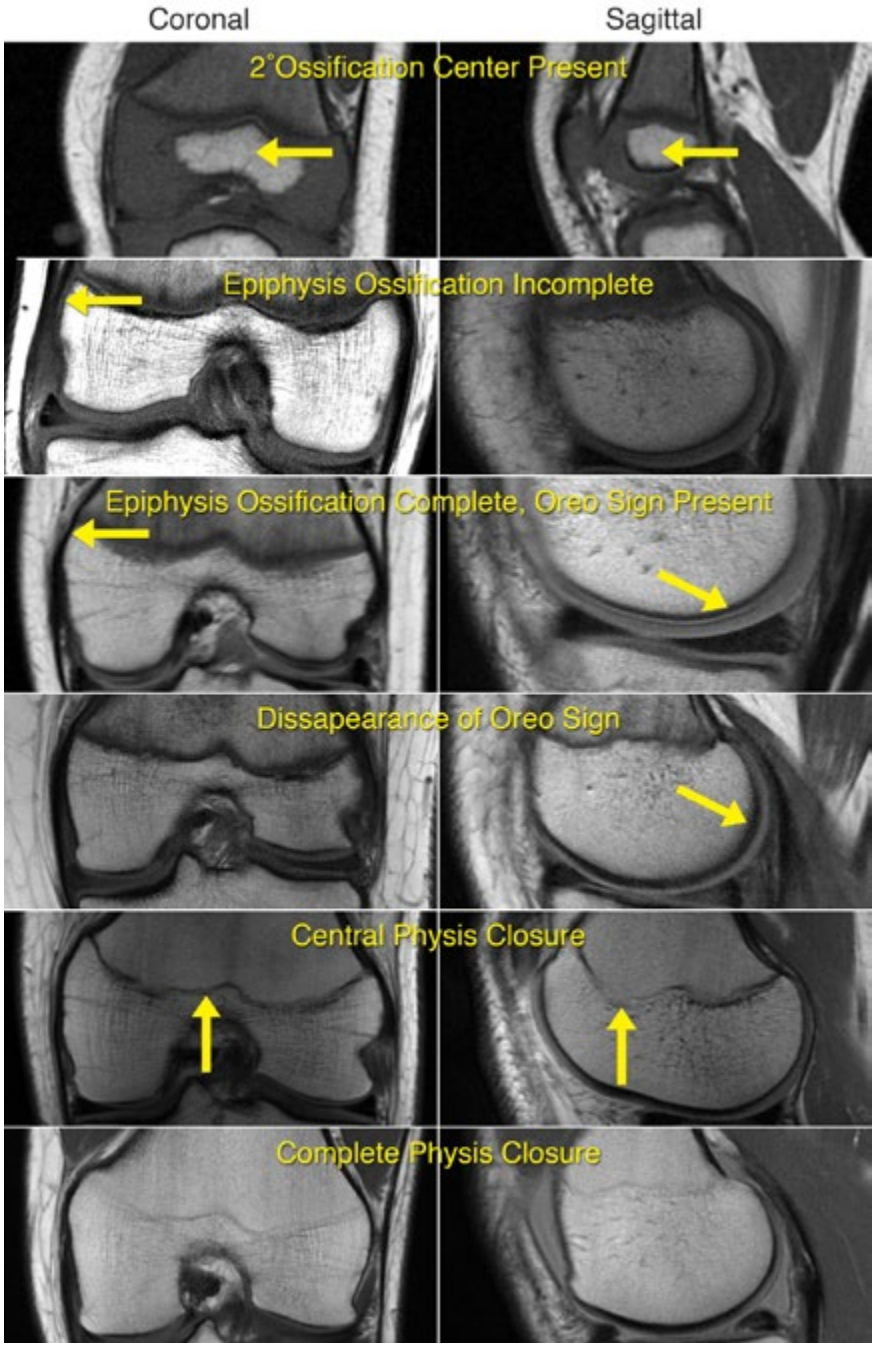


The sagittal slice through the center of the medial femoral condyle was selected



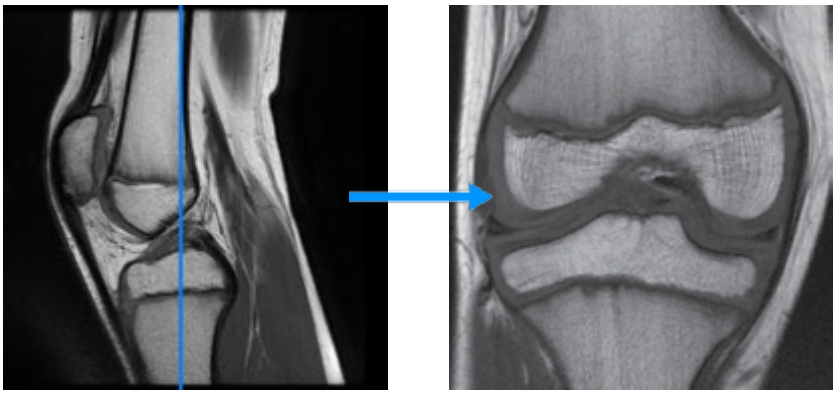
Femur Specific Features

The following features of the femur were identified: the presence of the epiphyseal secondary (2°) ossification center, complete ossification of the epiphysis, disappearance of the laminated appearance of the subchondral epiphyseal cartilage (termed the “Oreo” sign), narrowing of the physis, partial closure of the physis, and complete closure of the physis.

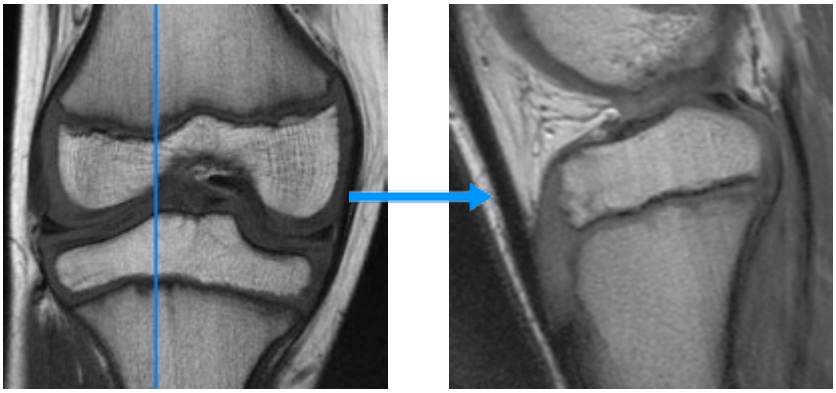


Tibia Slice Standardization

The coronal slice at the attachment site of the ACL on the femur where the tibial spines are most pronounced should be selected.

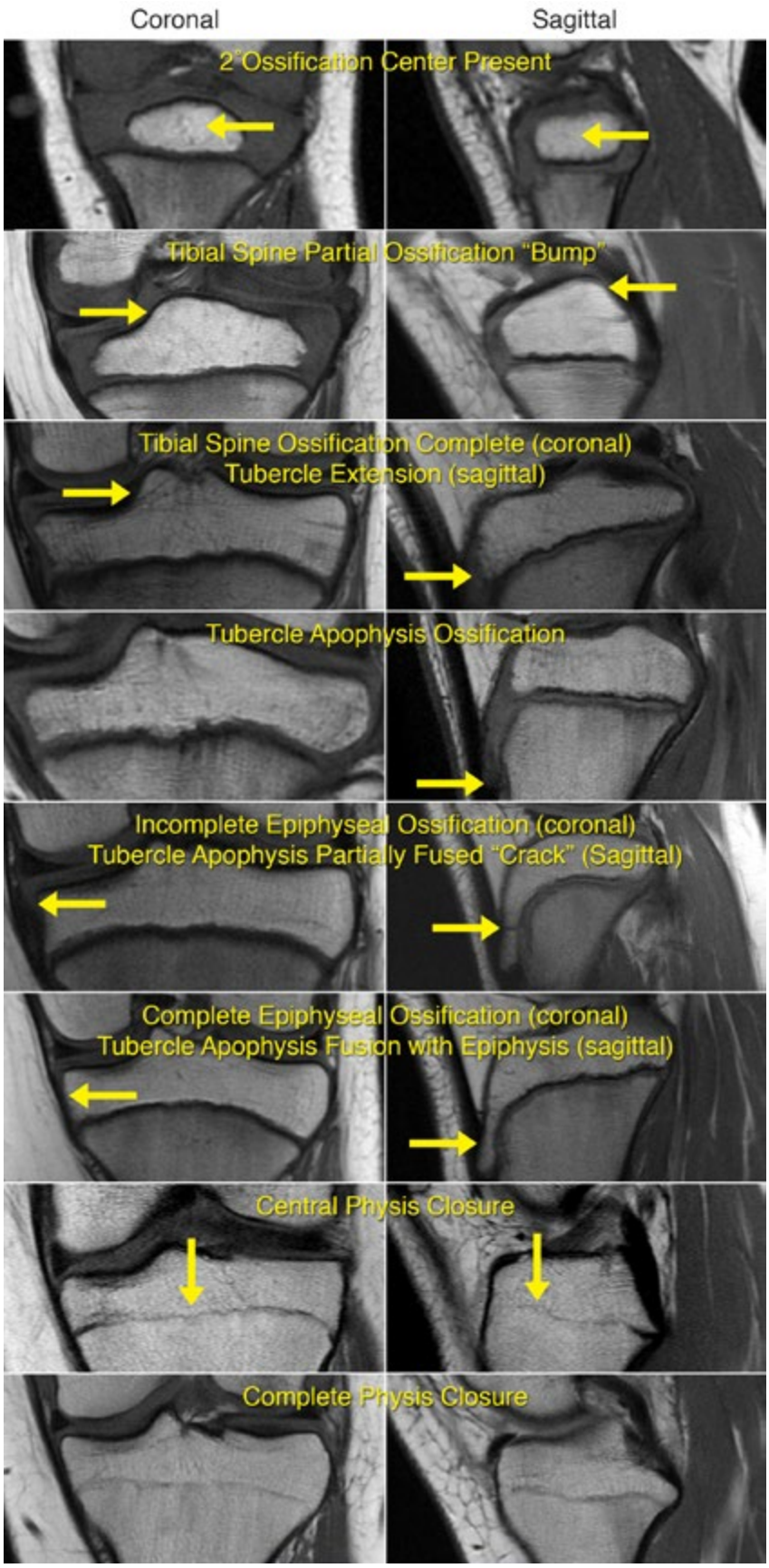


The sagittal slice through the center of the tibial tubercle should be selected



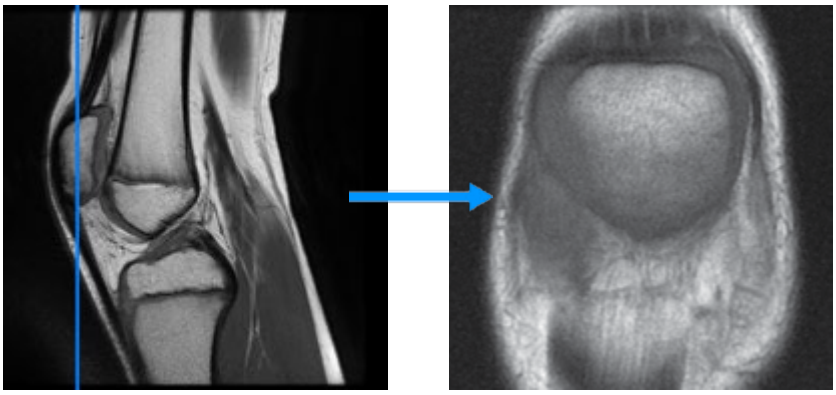
Tibia Specific Features

The following features of the tibia were identified: the presence of the epiphyseal secondary ossification center, partial ossification of the tibial spine (which appears as a “bump” on the coronal image), complete ossification of the tibial spine, anterodistal epiphyseal ossification extension toward the tubercle apophysis, appearance of the distal tubercle apophysis ossification center, fusion of the tubercle apophysis ossification center with the epiphysis (just prior to fusion of the tubercle apophysis with the epiphysis, a “crack” can be observed during a narrow window of skeletal maturity), complete ossification of the epiphysis, narrowing of the physis, partial closure of the physis, and complete closure of the physis.

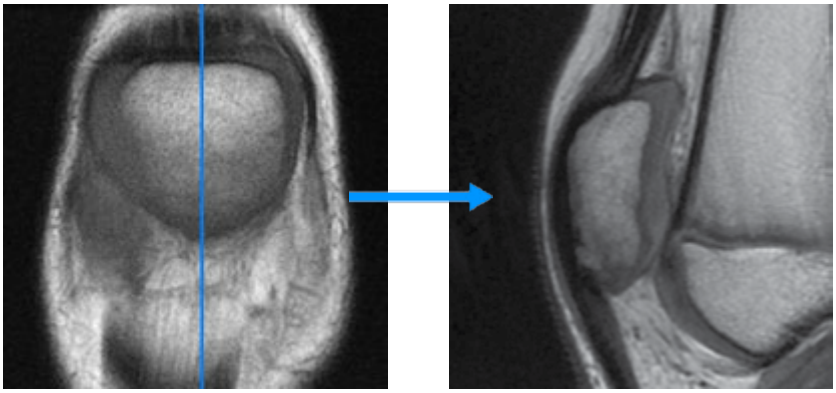


Patella Slice Standardization

The coronal slice was selected through the center of the patella where the patella was longest in the proximal to distal direction on the sagittal view and where the patella was widest in the medial to lateral direction on the coronal view.

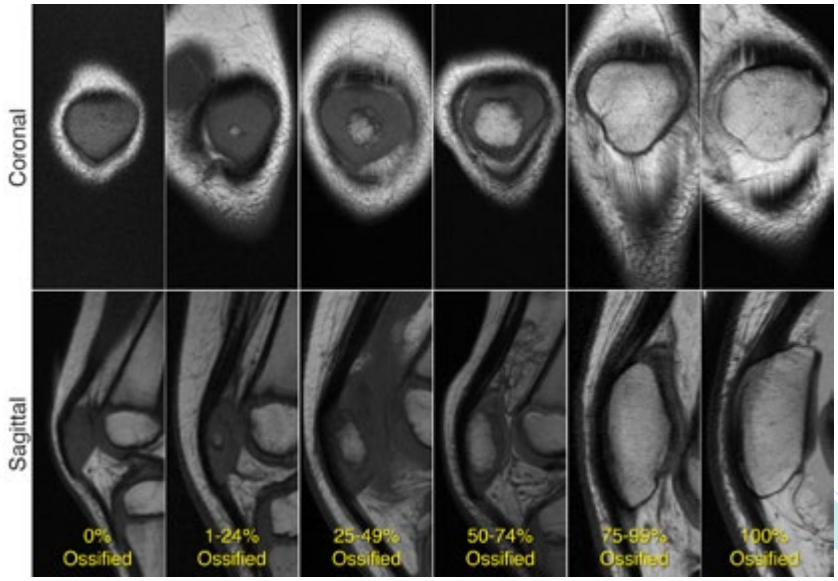


The sagittal slice was selected through the center of the patella where the patella was longest in the proximal to distal direction.



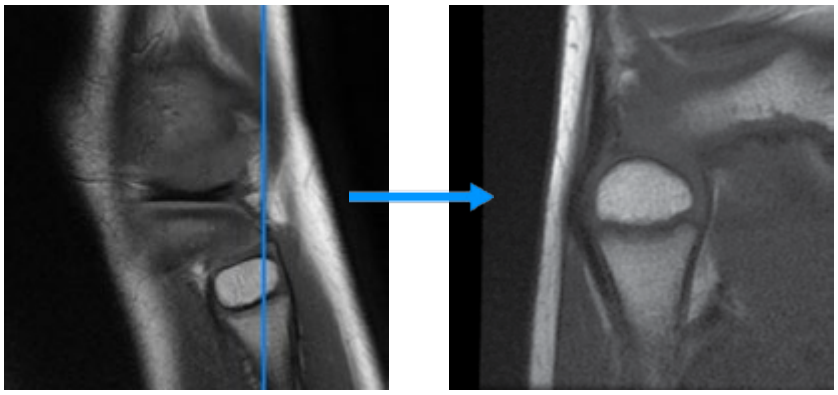
Patella Specific Features

An ossification percentage was calculated on the basis of the amount of ossification within the patella. This calculation was performed using both the coronal and sagittal images. Patients were then grouped according to the percentage of ossification present: 0%, 1% to 24%, 25% to 49%, 50% to 74%, 75% to 99%, or 100% (complete) ossification. Of note, the last portion of the patella to ossify was its superior tip, which was best visualized on the sagittal image.

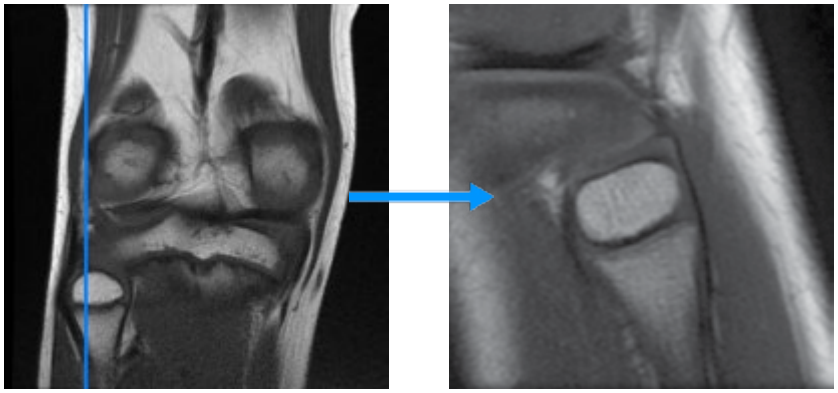


Fibula Slice Standardization

The coronal slice through the center of the fibular styloid was selected.

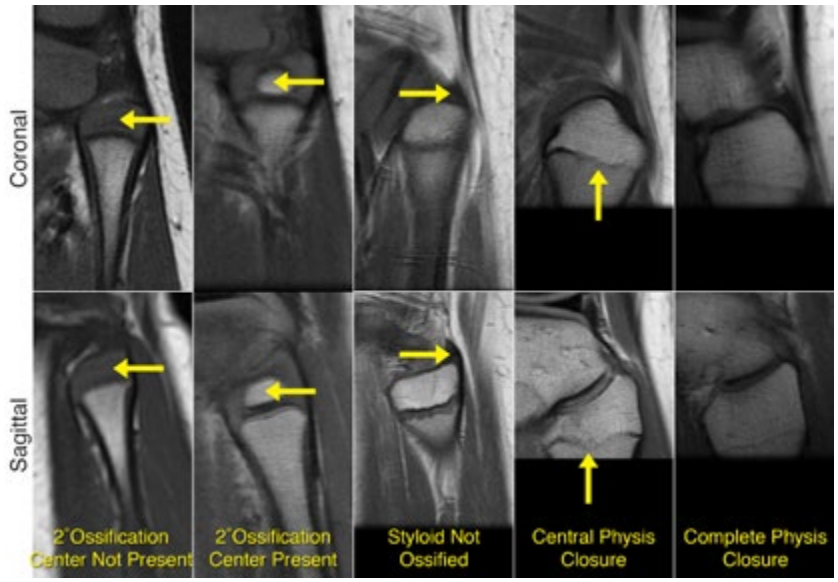


The sagittal slice through the center of the fibular styloid was selected



Fibula Specific Features

The following features of the fibula were identified: the presence of the epiphyseal secondary ossification center, complete epiphyseal ossification (other than the styloid), ossification of the fibular styloid tip, partial closure of the physis, and complete closure of the physis.



Standard Reference Creation

To create a standard of reference for each age and each gender, we repeatedly ordered approximately 30 patients (when available) for each age and gender from least mature to most mature. The patient determined to be in the middle of the maturity spectrum was identified as the “standard”. The atlas “standard” consists of 8 images, including both coronal and sagittal images, of the femur, tibia, patella, and fibula.

If a clinician wishes to determine the skeletal maturity of a knee MRI compared to the standard atlas, we recommend that they proceed to the age and gender "standard" corresponding to the chronologic age of the patient. By comparing the standardized coronal and sagittal slices from each bone of their patient to this "standard" as well as to the standard immediately preceding and following the selected age, one can rapidly determine whether the patient's skeletal age corresponds approximately with the age in this standard of reference.

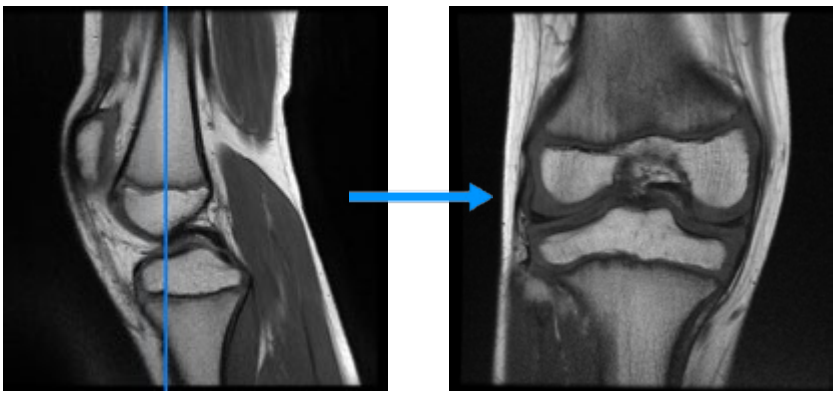
If the clinician does not know the patient's age whose MRI they wish to assess, the clinician may look through the atlas until they come to the standard that most closely resembles their patient. Similar to the Greulich and Pyle Hand atlas, the clinician will occasionally find that the MRI features of a patient resemble two successive standards. In these situations, we recommend that that clinician use all available bones (femur, tibia, patella, and fibula) and images (coronal and sagittal) to best match the patient to the standard.

Proper Image Selection

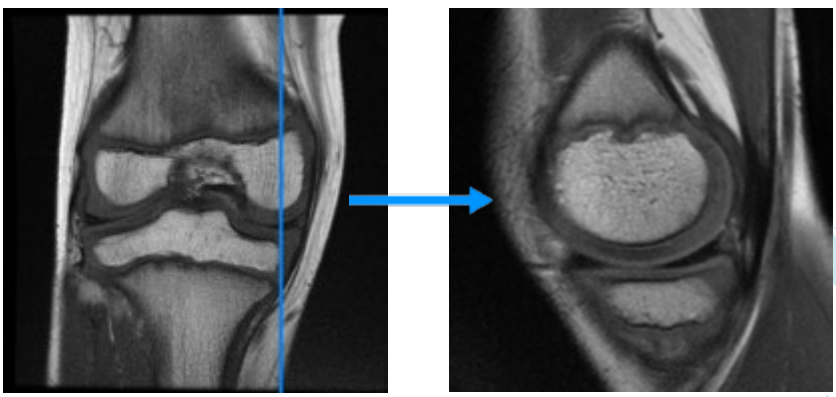
Slice selection for use of the atlas is performed in the identical fashion as *Slice Standardization* in creating the atlas, as described in pages 9-14. Many of the MRI indicators or features identified in this Atlas are subtle making appropriate image selection essential for each individual bone and for each image sequence (coronal and sagittal). The following slides depict which image should be selected for each bone.

Slice Selection: Femur

The coronal slice through the center of the distal aspect of the femur at the attachment site of the posterior cruciate ligament on the medial femoral condyle was selected.

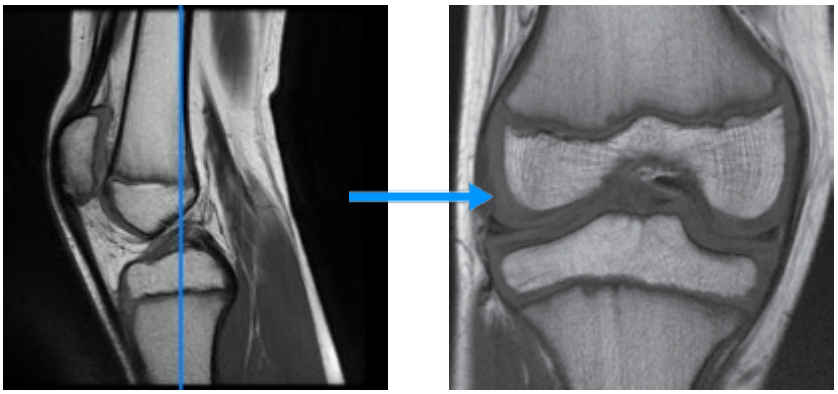


The sagittal slice through the center of the medial femoral condyle was selected

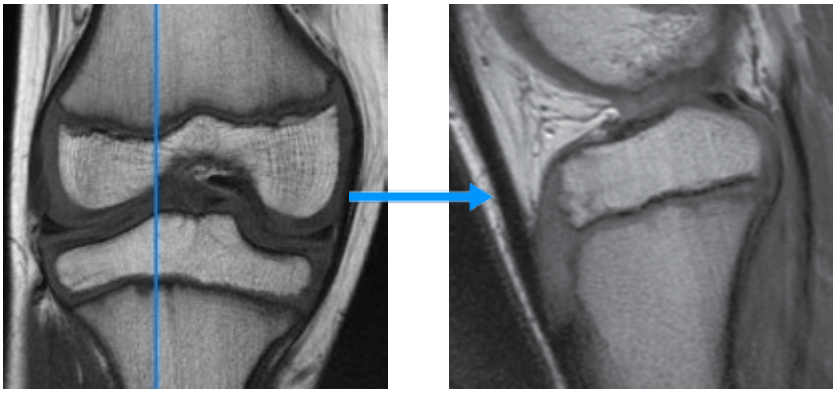


Slice Selection: Tibia

The coronal slice at the attachment site of the ACL on the femur where the tibial spines are most pronounced should be selected.

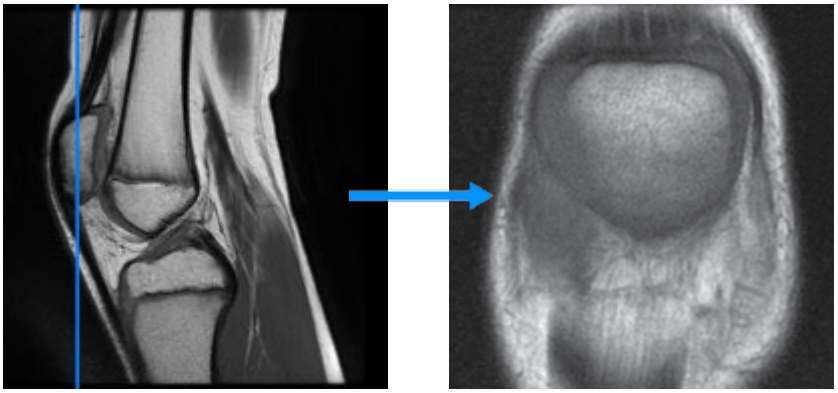


The sagittal slice through the center of the tibial tubercle should be selected

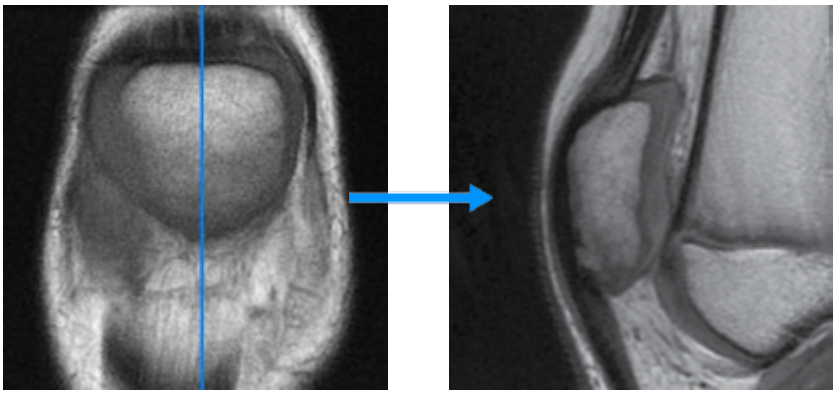


Slice Selection: Patella

The coronal slice was selected through the center of the patella where the patella was widest in the medial to lateral direction.

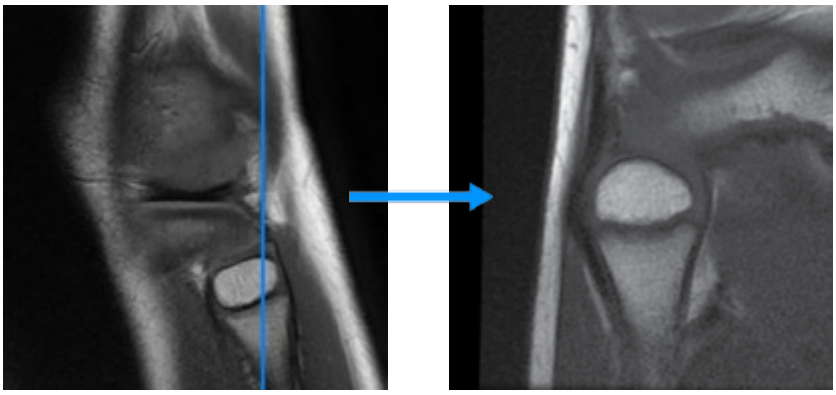


The sagittal slice was selected through the center of the patella where the patella was longest in the proximal to distal direction.

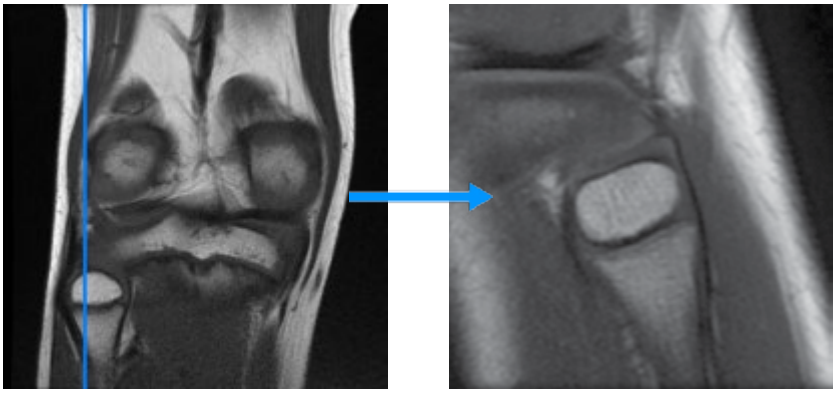


Slice Selection: Fibula

The coronal slice through the center of the fibular styloid was selected.

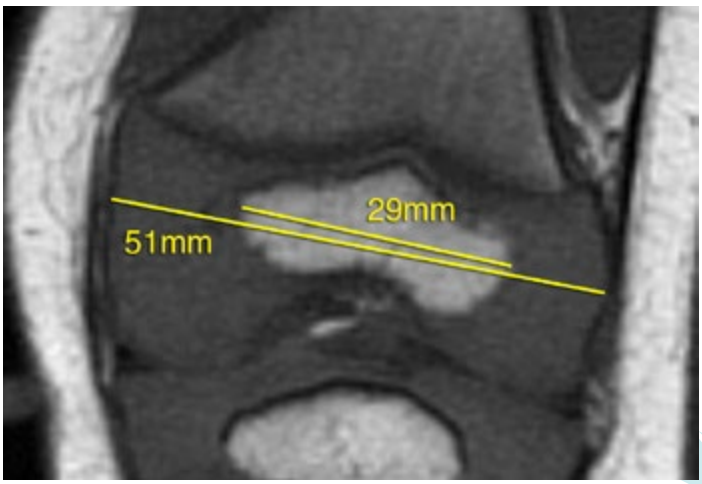


The sagittal slice through the center of the fibular styloid was selected



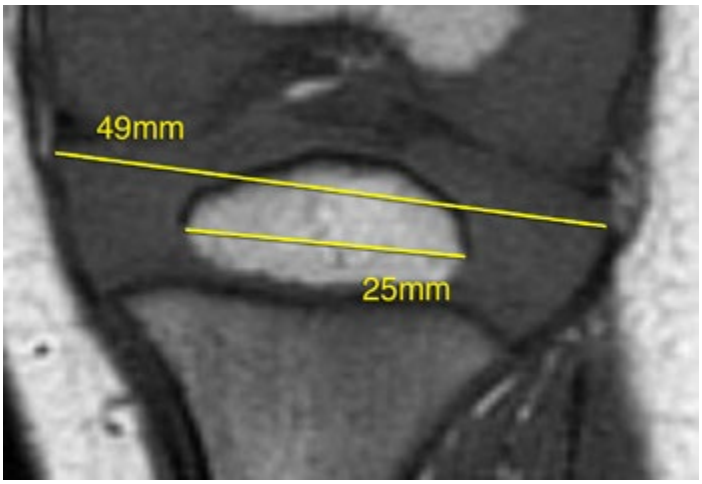
Percent Ossification Measurement: Femur

Femoral ossification is measured on the coronal view as a percentage of the width of the entire distal femur (both the ossified and unossified portions of the bone) compared to the ossified portion. In this case, 57% of the femur is ossified (29mm/51 mm).



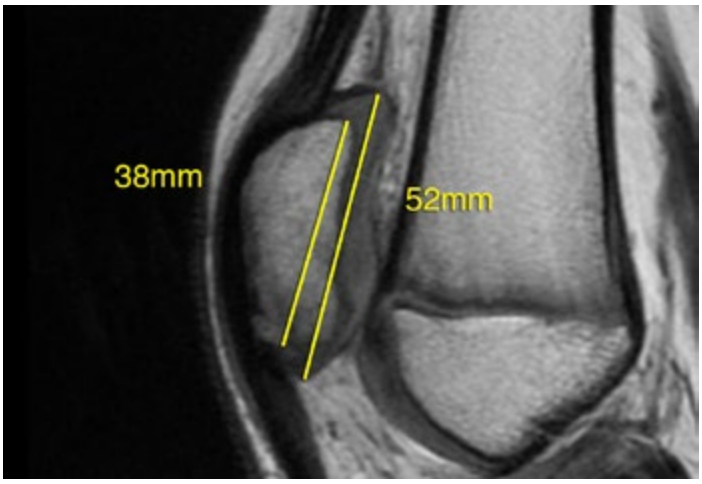
Percent Ossification Measurement: Tibia

Tibial ossification is measured on the coronal view as a percentage of the width of the entire proximal tibia (both the ossified and unossified portions of the bone) compared to the ossified portion. In this case, 51% of the tibia is ossified (25mm/49mm).



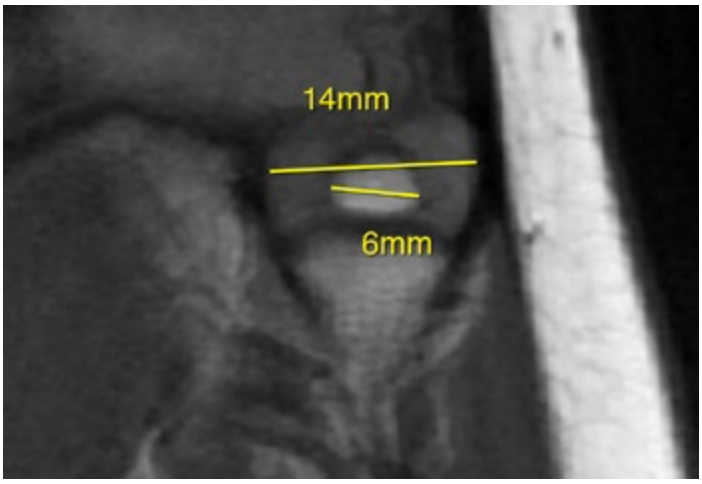
Percent Ossification Measurement: Patella

The patellar ossification is measured on the sagittal view as a percentage of the length of the entire patella (both the ossified and unossified portions of the bone) compared to the ossified portion. In this case, 73% of the patella is ossified (38mm/52 mm).



Percent Ossification Measurement: Fibula

Fibular ossification is measured on the coronal view as a percentage of the width of the entire proximal fibula (both the ossified and unossified portions of the bone) compared to the ossified portion. In this case, 43% of the fibula is ossified (6mm/14mm).



Quick Reference

As a quick reference, we have identified the median ages for each gender as to when specific MRI features become apparent. This table can serve as an expedited means of aging patients.

Key radiographic features of the patella, fibula, tibia, and femur and their appearance and disappearance. Numbers reported are in years.

	Male			Female		
	1st	Median	All	1st	Median	All
Femur 2˚ ossification center present	Present in all subjects			Present in all subjects		
Complete ossification of femoral epiphysis	10.1	14.2	15.5	9.8	11.9	12.3
Disappearance of "oreo sign"	13.4	15.6	16.9	11.7	13.9	15.0
Central physis closure	14.7	16.9	17.7	12.9	15.15	16.2
Complete physis closure	15.1	18.7	19.8	14.7	17.1	18.3
Tibia 2˚ ossification center present	Present in all subjects			Present in all subjects		
Partial ossification of tibial spine "bump"	5.1	6.9	9.9	4.0	5.9	8.0
Complete ossification of tibial spine	8.1	9.1	10.0	5.3	7.1	8.1
Tubercle extension of epiphysis	8.2	10.2	11.0	6.1	7.3	8.1
Tubercle apophysis ossification	10.1	11.8	12.6	7.3	10.15	11.5
Partial fusion of tubercle apophysis "crack"	11.8	12.8	14.9	9.0	10.7	11.9
Complete ossification of tibial epiphysis	12.1	14.55	16.0	9.8	11.9	12.3
Central physis closure	14.7	16.05	16.9	12.4	14.3	15.0
Complete physis closure	14.7	18.0	19.8	13.3	16.2	17.2
Patella ossified <25%	3.0	4.7	7.9	2.5	3.3	3.4
25-49%	4.0	5.5	7.8	3.2	4.0	5.7
50-74%	5.4	7.3	9.9	4.0	5.75	7.7
75-99%	6.9	10.7	15.0	5.3	8.95	11.5
Complete ossification of patella	10.1	13.7	15.1	9.8	11.85	12.3
Fibula 2˚ ossification center present	3.0	4.2	4.9	2.5	4.0	4.7
Fibular styloid ossified	14.0	15.6	16.9	12.1	13.25	13.9
Central physis closure	14.7	16.7	17.7	12.9	15.2	17.0
Complete physis closure	15.1	18.1	19.8	14.7	16.75	18.0

Anatomic and Radiographic Terms

Several MRI indicators used in this atlas may be unfamiliar to clinicians. Additionally, some of the terms such as tibial tubercle “crack” and the femoral “oreo sign” have not been clinically used. In the following figures, we hope to clarify these important findings to make them easier to recognize and anatomically understand.

Femoral “Oreo” Sign

- During a relatively narrow window of skeletal development the epiphyseal cartilage immediately adjacent to the articular cartilage has an oreo appearance.
- For boys this disappears at a median age of 15.6 years (range 13.4-16.9)
- For girls this disappears at a median age of 13.9 years (range 11.7-15.0)

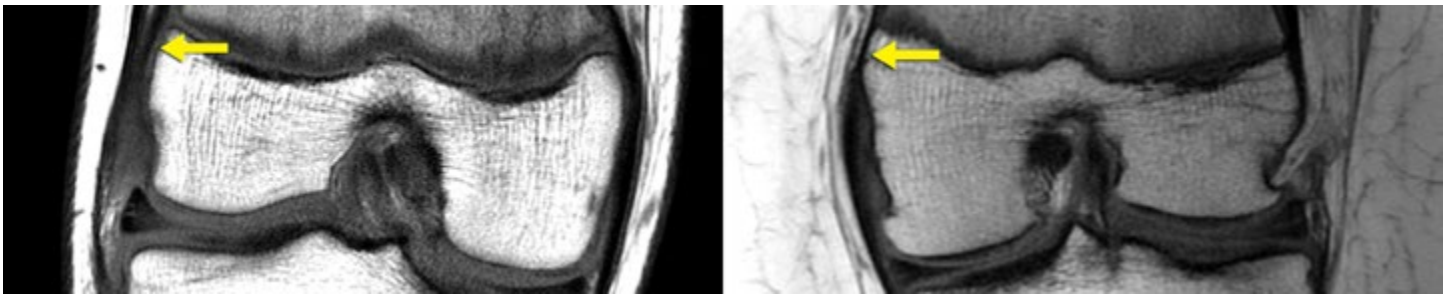
9 year-old boy | **13.5 year-old boy** | **15.5 year-old boy**

Presence of “Oreo” sign | **Presence of “Oreo” sign** | **Disappearance of “Oreo” sign**

Complete Ossification of the Femoral Epiphysis

- Unossified cartilage that may be appreciated on coronal imaging, immediately adjacent to the medial and lateral epicondyles, is another maturity marker on the knee.
- For boys this cartilage completely ossifies at a median age of 14.2 years (range 10.1-15.5)
- For girls this cartilage completely ossifies at a median age of 11.9 years (range 9.8-12.3)

14 year-old boy | **15 year-old boy**

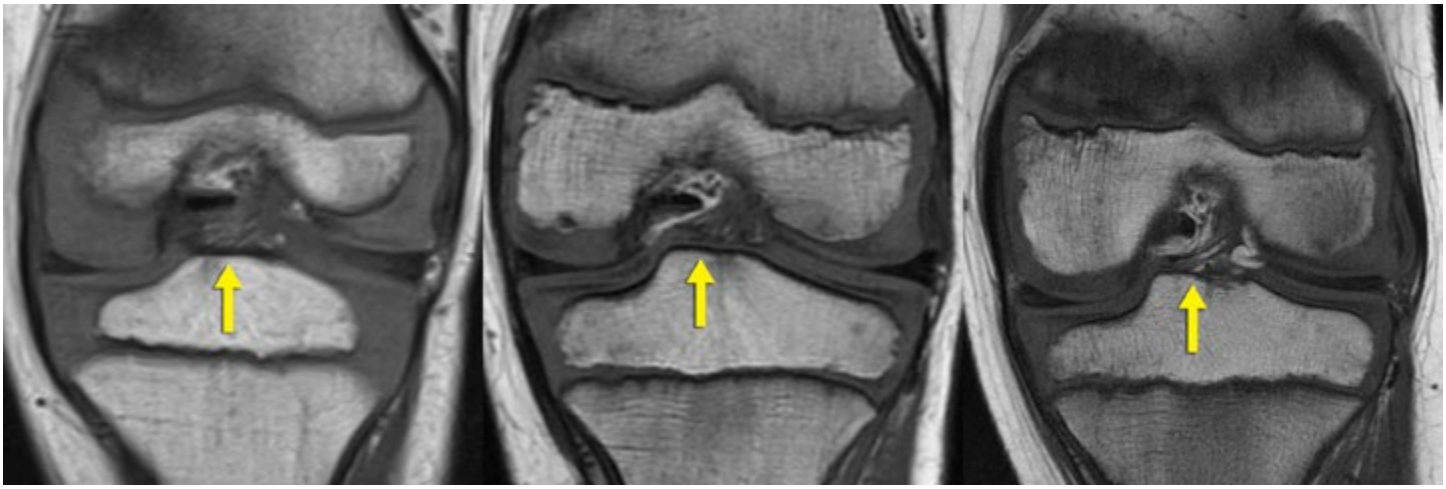


Incomplete Ossification | **Complete Ossification**

Tibial Spine "Bump"

- The ossification of the tibial spines progresses through reproducible phases. Initially, no ossification is present. At a median age of 6.9 years for boys and 5.9 for girls, the initial ossification of the spines represents a "bump" which then progresses to complete ossification at age 9.1 for boys and 7.1 for girls

6 year-old boy **8 year-old boy** **9 year-old boy**



No "bump" present **"Bump" present** **Spines present**

Tibial Tubercle Epiphyseal "Extension"

- As the tubercle begins to ossify, the anterior epiphysis begins "extending" distal and below the level of the physis.
- For boys, this occurs at a median age of 10.2 years (range 8.2-12.2)
- For girls, this occurs at a median age of 7.3 years (range 6.1-8.1)

10 year-old boy **11.5 year-old boy**

No tubercle "extension" **Tubercle "extension"**

Tibial Tubercle Ossification versus "Crack"

- As the tubercle apophysis appears (median age 11.8 years for boys and 10.2 years for girls), ossification can first be identified distally. The tubercle epiphyseal extension and the apophyseal ossification then merge giving the appearance of a "crack" which occurs in boys at a median age of 12.8 years and girls at 10.7 years

12 year-old boy **13 year-old boy** **14 year-old boy**

Tubercle apophysis ossification **"Crack"** **Complete ossification**

Complete Ossification of the Tibial Epiphysis

- The last portions of the tibial epiphysis to ossify can be seen best on coronal imaging medially and sagittal imaging posteriorly.
- For boys this cartilage completely ossifies at a median age of 14.6 years (range 12.1-16.0)
- For girls this cartilage completely ossifies at a median age of 11.9 years (range 9.8-12.3)

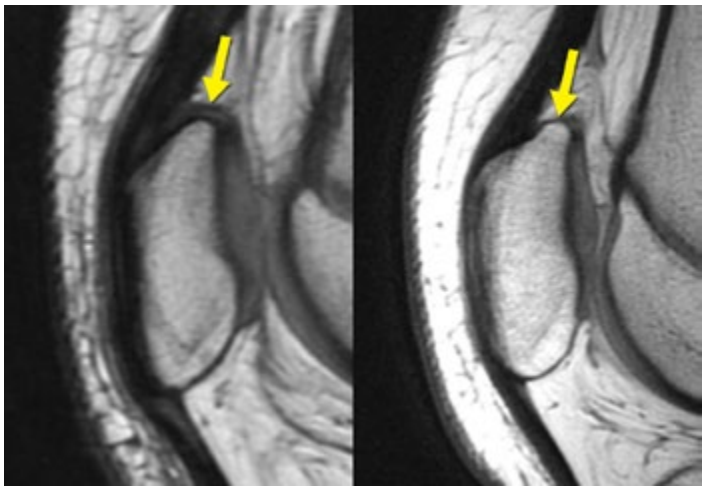
14 year-old boy **15 year-old boy** **14 year-old boy** **15 year-old boy**

Incomplete ossification **Complete ossification** **Incomplete ossification** **Complete ossification**

Patella Superior Tip Ossification

- The last portion of the patella to ossify is the patella tip which ossifies at a median age of 13.7 years (range 10.1-15.1) for boys and a median age of 11.9 years (range 9.8-12.3) for girls.

12 year-old boy **14 year-old boy**

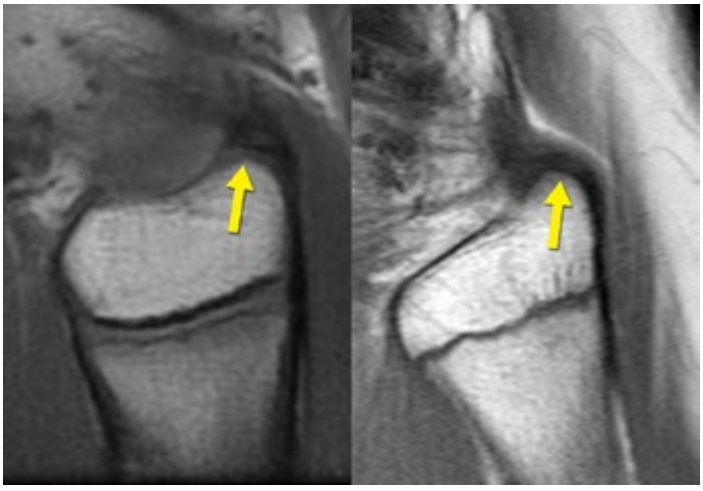


Incomplete ossification **Complete ossification**

Fibular Styloid Ossification

- The fibular styloid is the last portion of the fibula to ossify and occurs at a median age of 15.6 years for boys and 13.3 years for girls.

14 year-old boy **16 year-old boy**



Fibular styloid unossified **Fibular styloid ossified**

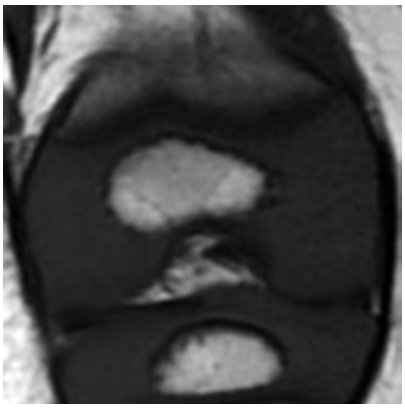
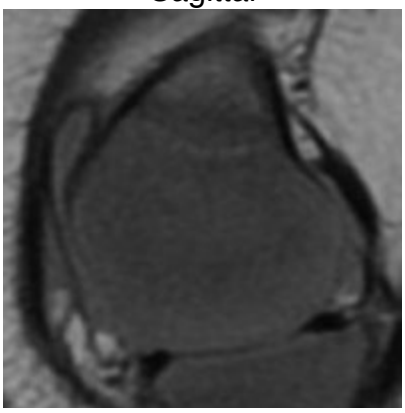
Female Standard – Age 1 Year

Coronal | Sagittal

Femur

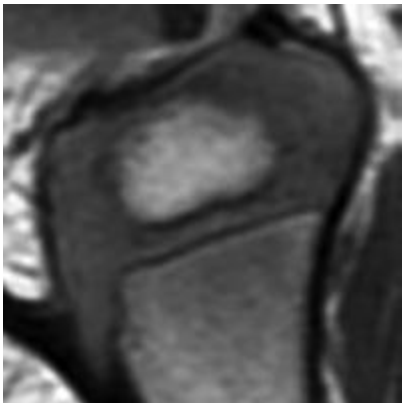
Incomplete ossification

No ossification visible through center of the medial femoral condyle on the sagittal view

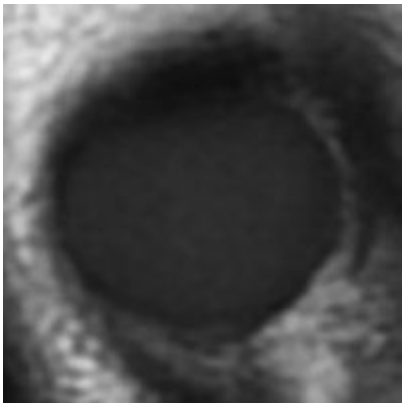
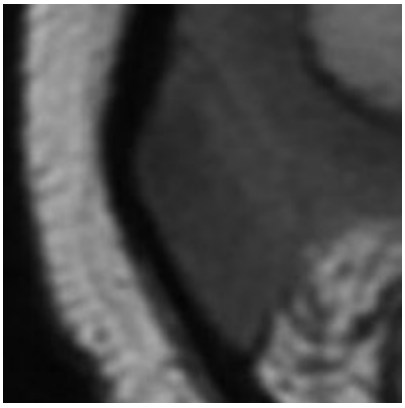
Tibia

Incomplete ossification

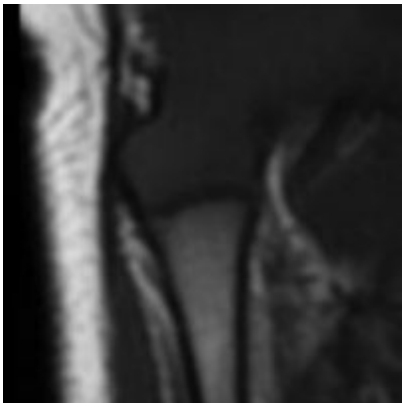
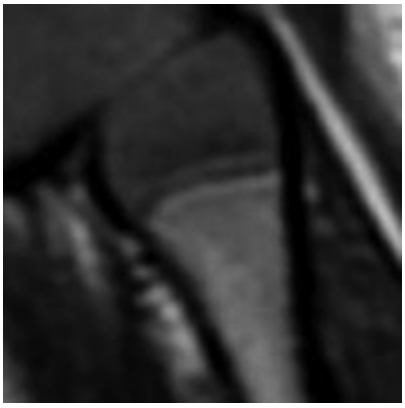
Patella

No ossification

Fibula

No epiphyseal ossification

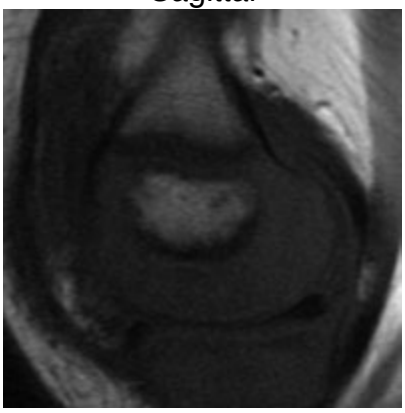



Female Standard – Age 2 Years

Coronal | Sagittal

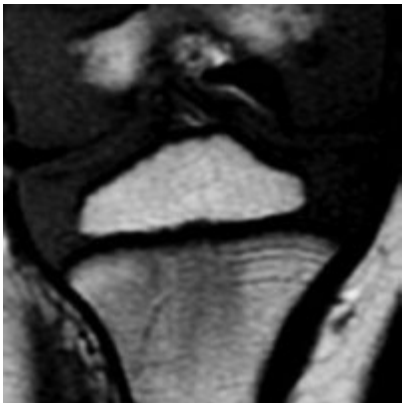
Femur

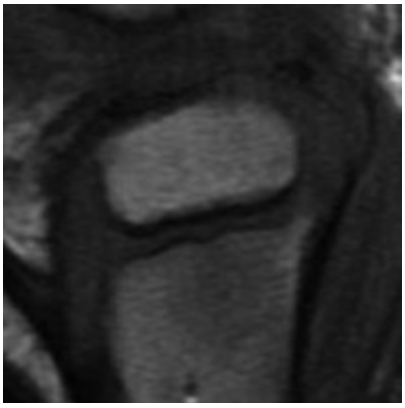
Incomplete ossification
(50-75%)



Tibia

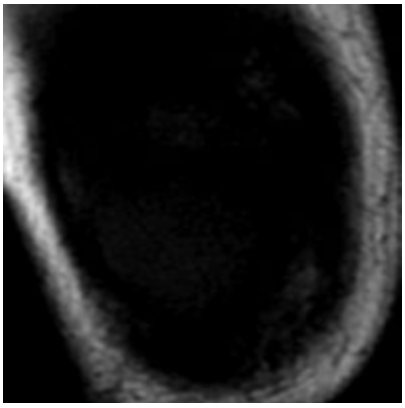
Incomplete ossification
(50-75%)

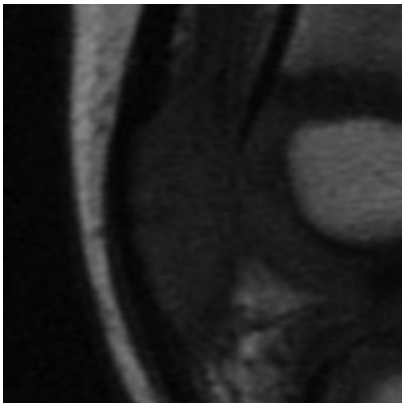




Patella

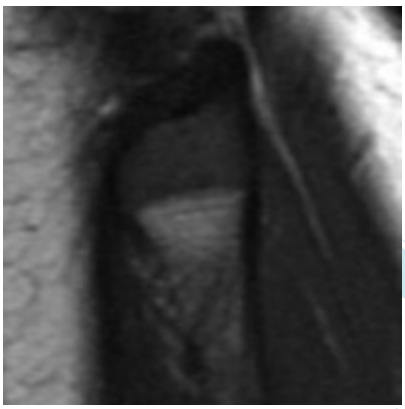
No ossification





Fibula

No epiphyseal ossification



Female Standard – Age 3 Years

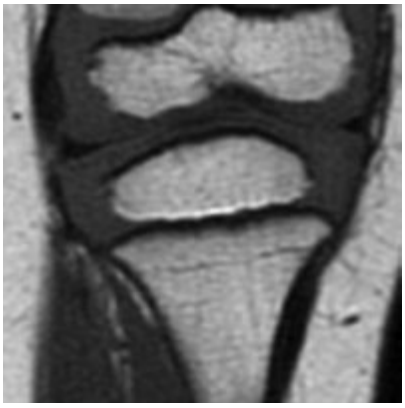
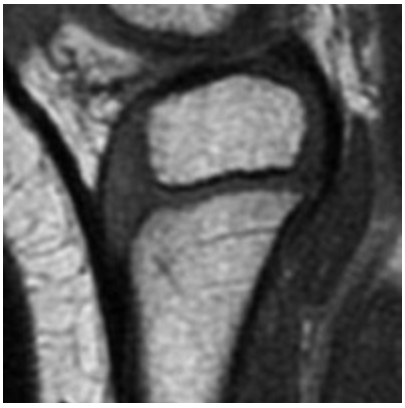
Coronal | Sagittal

Femur

Incomplete ossification
(75-90%)

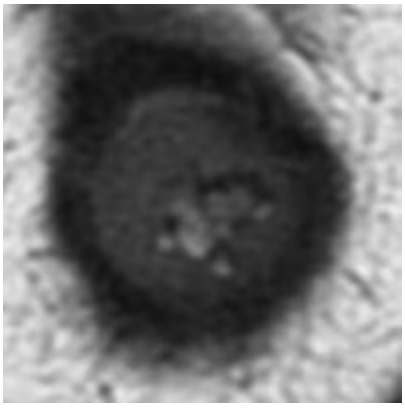
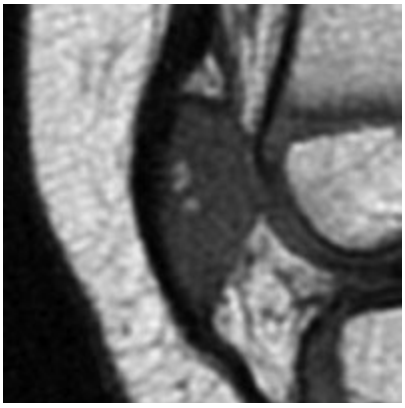

Tibia

Incomplete ossification
(50-75%)

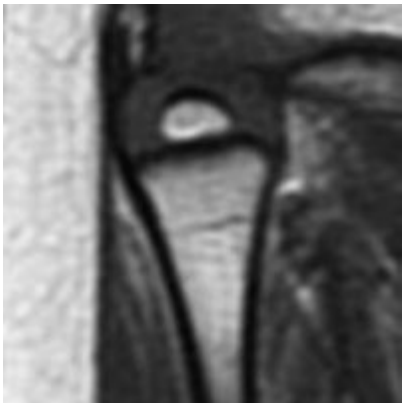
Patella

Incomplete ossification
(0-25%)

Fibula

No ossification or
Incomplete ossification




Female Standard – Age 4 Years

Coronal | Sagittal

Femur

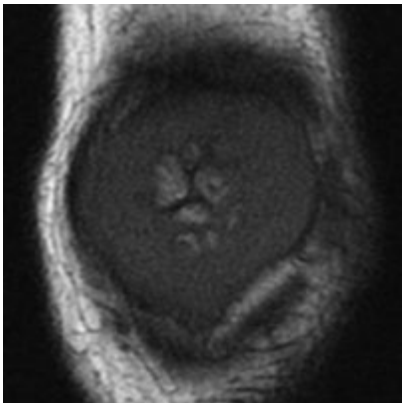
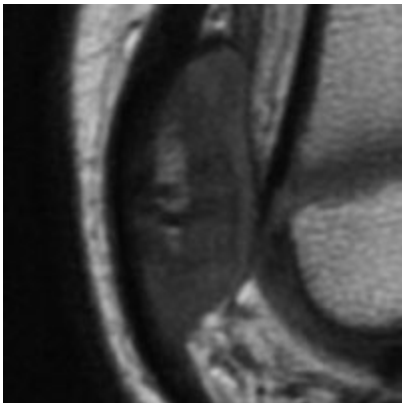
Incomplete ossification
(75-90%)


Tibia

Incomplete ossification
(50-75%)

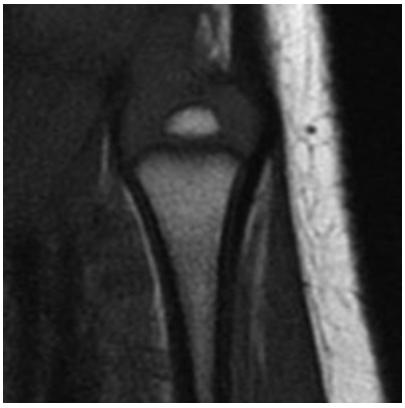
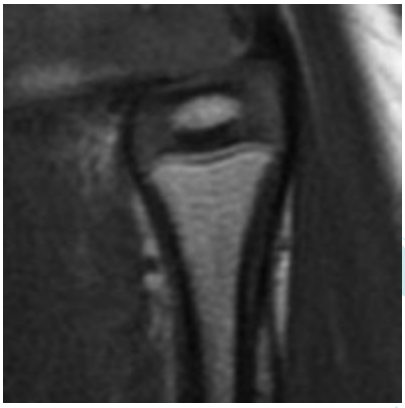

Patella

Incomplete ossification
(25-50%)

Fibula

Incomplete ossification
(25-75%)

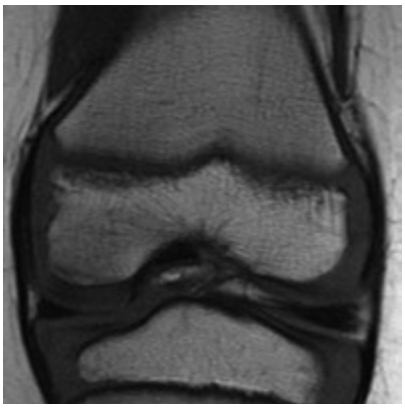
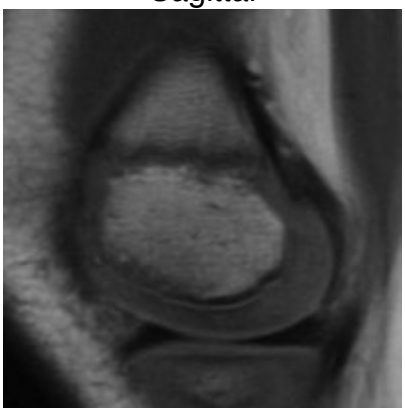



Female Standard – Age 5 Years

Coronal | Sagittal

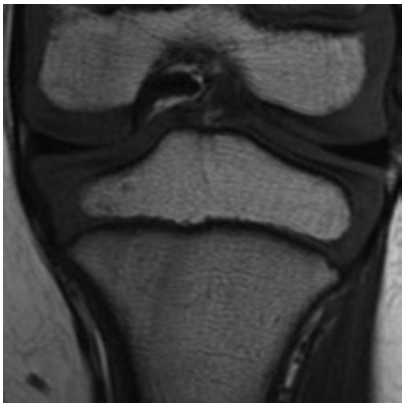
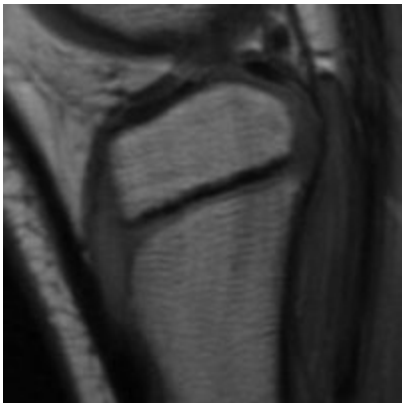
Femur

Incomplete ossification
(75-90%)

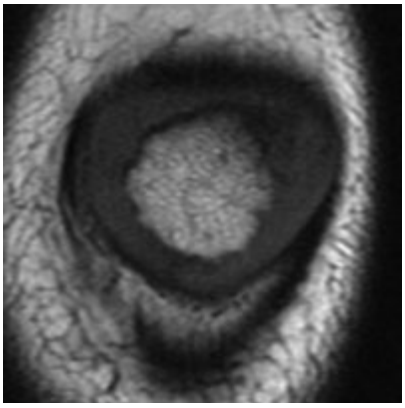
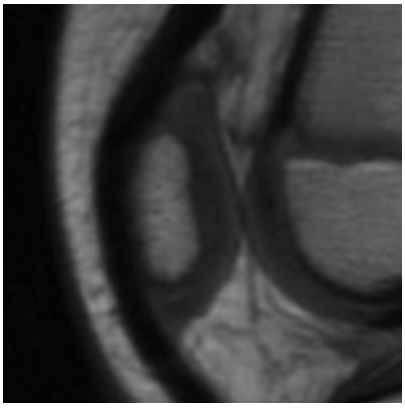
Tibia

Incomplete ossification
(75-90%)
Tibial spine “bump”

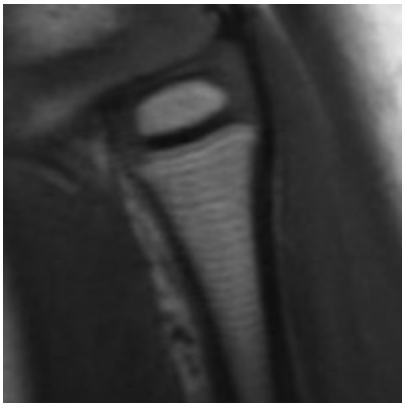
Patella

Incomplete ossification
(50-75%)

Fibula

Incomplete ossification
(25-75%)

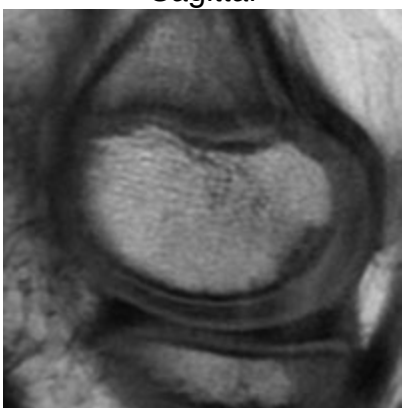



Female Standard – Age 6 Years

Coronal | Sagittal

Femur

Incomplete ossification
(>90%)
Oreo sign present

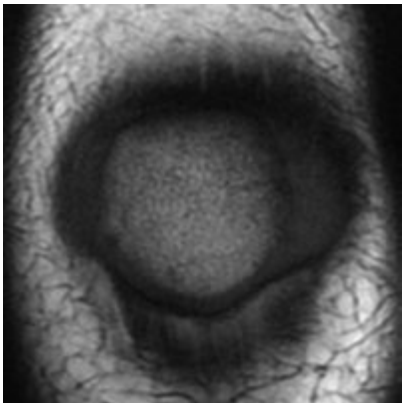
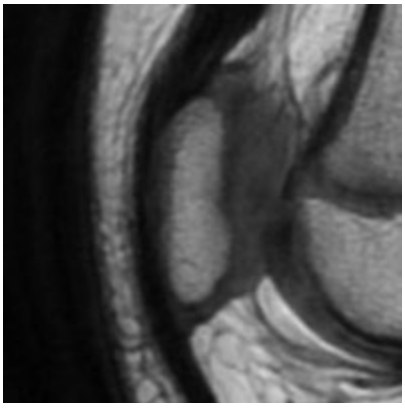



Tibia

Incomplete ossification
Tibial spine “bump”


Patella

Incomplete ossification
(>75%)
Superior and inferior tips

Fibula

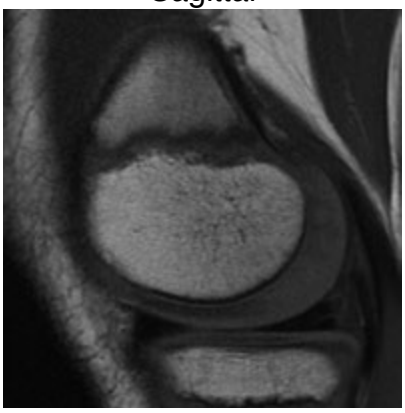
Incomplete ossification
(75-95%)


Female Standard – Age 7 Years

Coronal | Sagittal

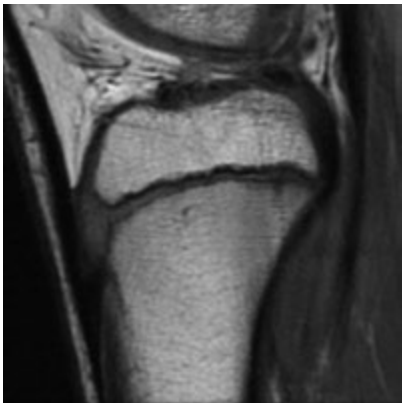
Femur

Incomplete ossification
(>90%)
Oreo sign present

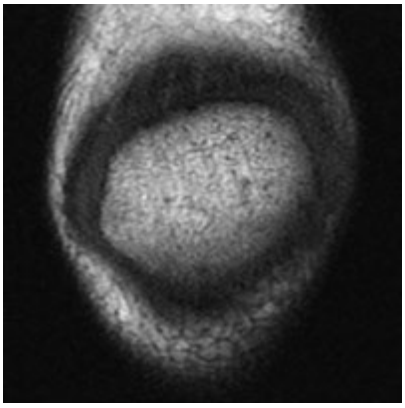
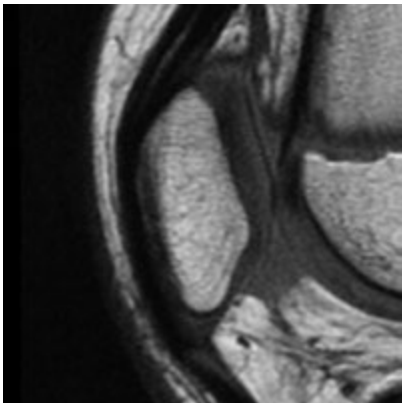
Tibia

Incomplete ossification
(>90%)
Tibial spine ossified

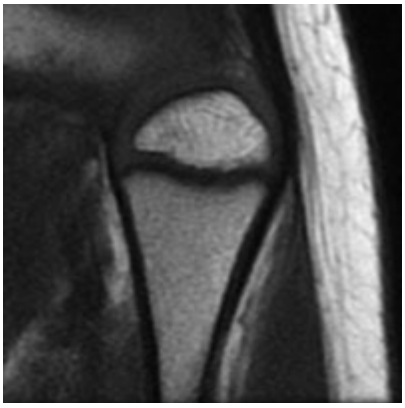
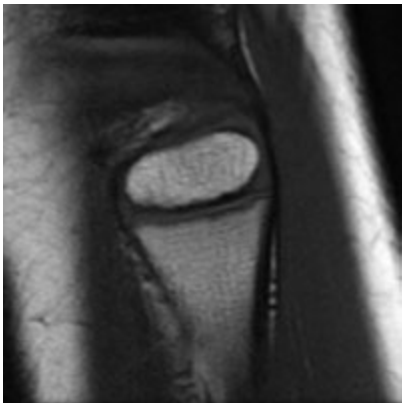
Patella

Incomplete ossification
(Superior and inferior tips)

Fibula

Incomplete ossification
Fibular styloid not ossified

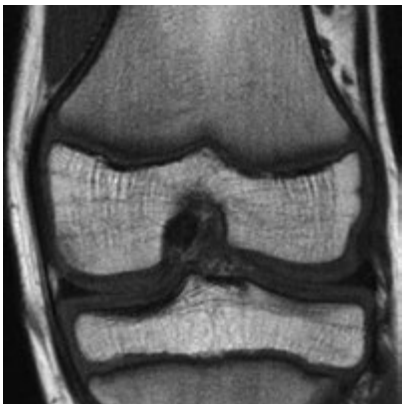



Female Standard – Age 8 Years

Coronal | Sagittal

Femur

Incomplete ossification
(Medially and laterally)
Oreo sign present

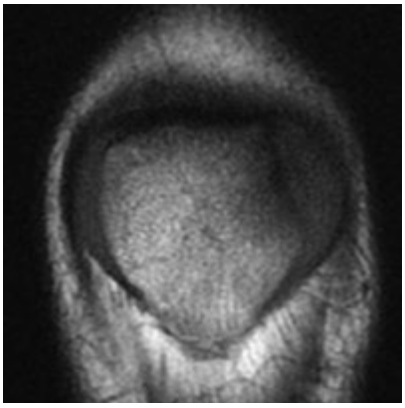
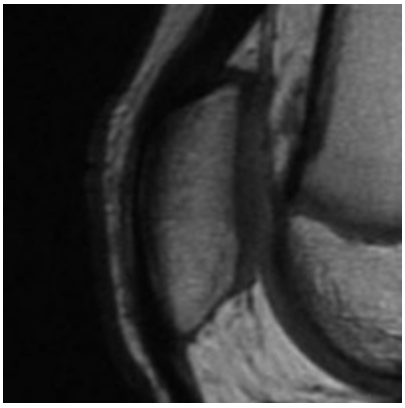



Tibia

Incomplete ossification
No apophyseal ossification
Tibial spine ossified
Tubercle epiphyseal extension

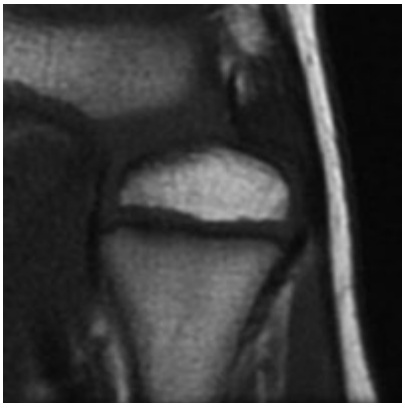
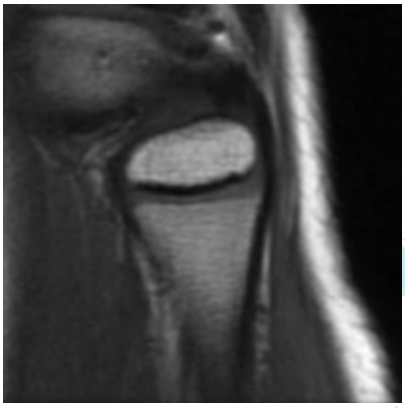

Patella

Incomplete ossification
(Especially superior tip)

Fibula

Incomplete epiphyseal ossification
Fibular styloid not ossified

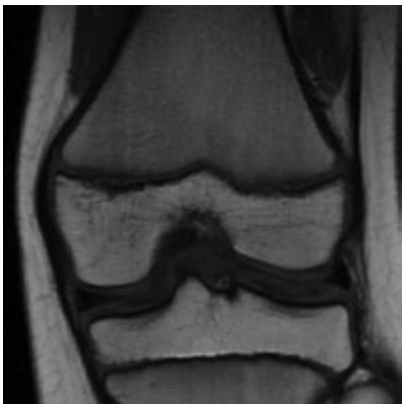
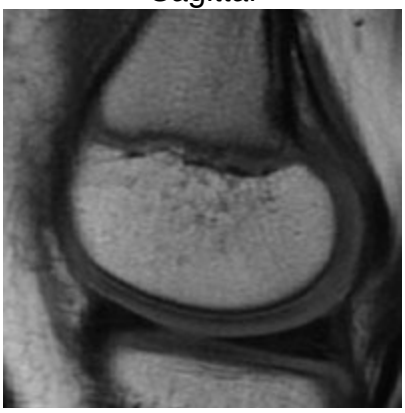



Female Standard – Age 9 Years

Coronal | Sagittal

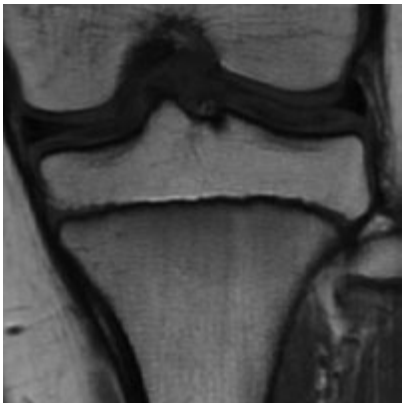
Femur

Incomplete ossification
(Medially and laterally)
Oreo sign present

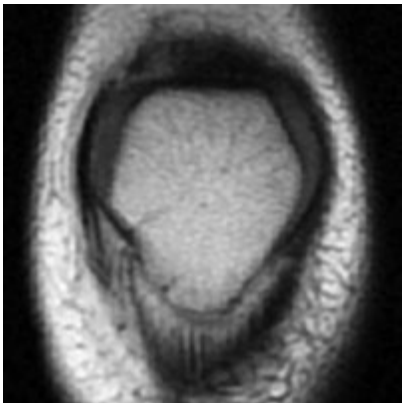
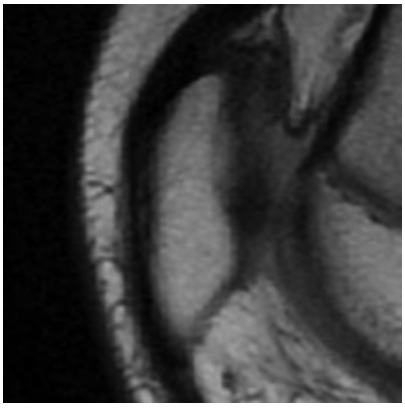
Tibia

Incomplete ossification
(Medially and laterally)
No apophyseal ossification
Tubercle epiphyseal extension



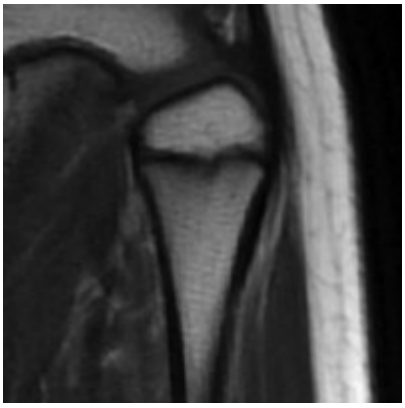
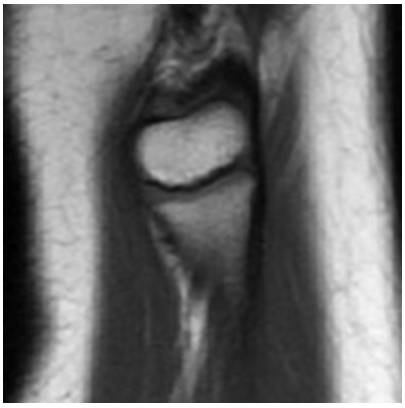

Patella

Incomplete ossification
(Especially superior tip)

Fibula

Incomplete epiphyseal ossification
Fibular styloid not ossified

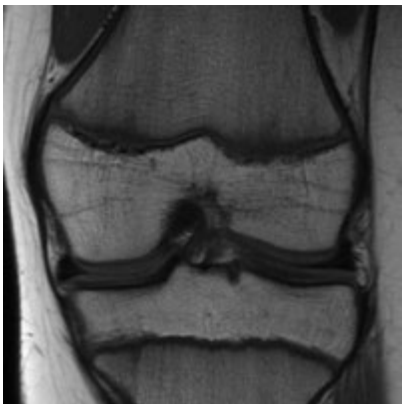
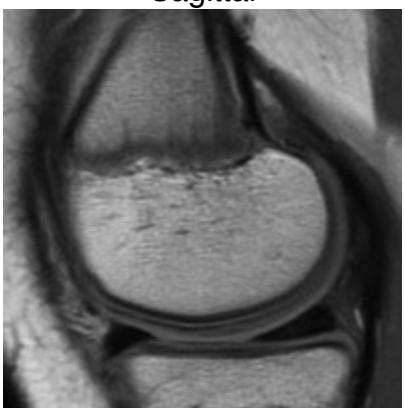



Female Standard – Age 10 Years

Coronal | Sagittal

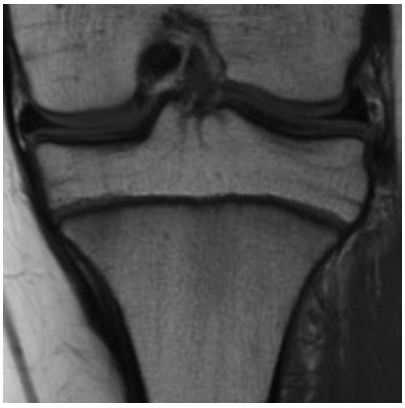
Femur

Incomplete ossification
(Especially medially)
Oreo sign present

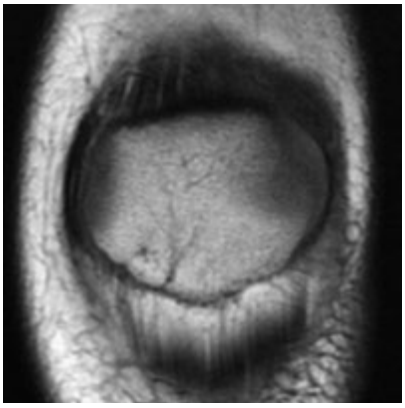
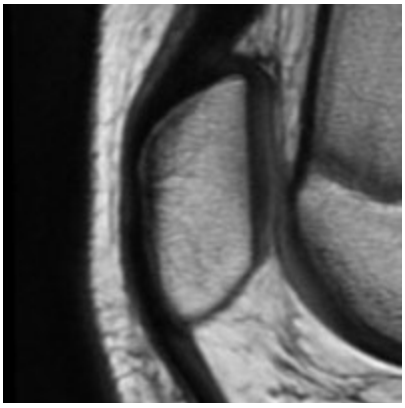
Tibia

Incomplete ossification
(Medially and posteriorly)
Apophysis ossification, but not fused



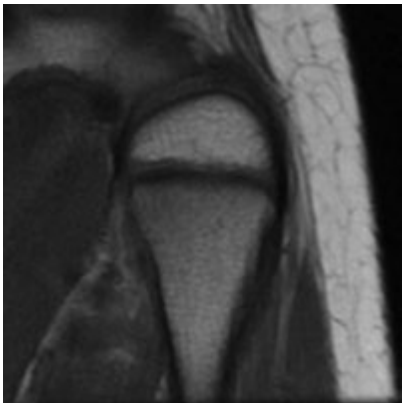
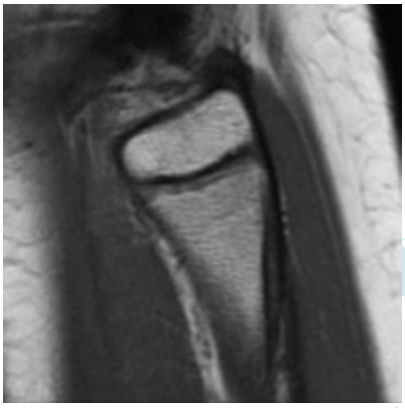

Patella

Incomplete ossification
(Especially superior tip)

Fibula

Fibular styloid not ossified

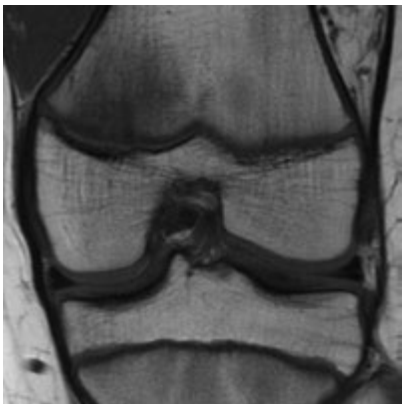
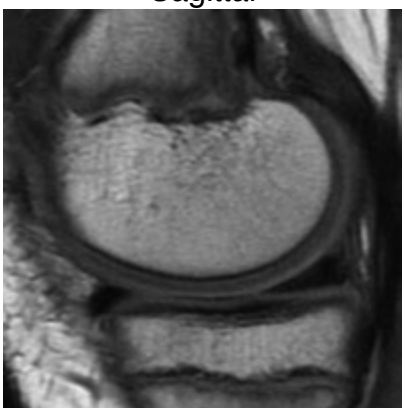



Female Standard – Age 11 Years

Coronal | Sagittal

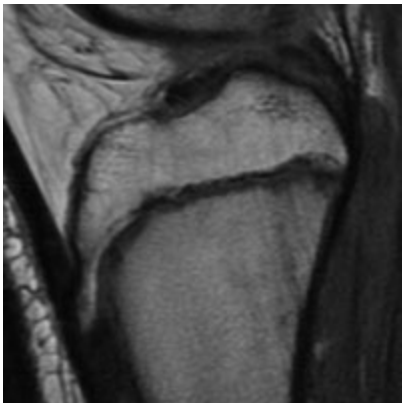
Femur

Complete ossification
Oreo sign present

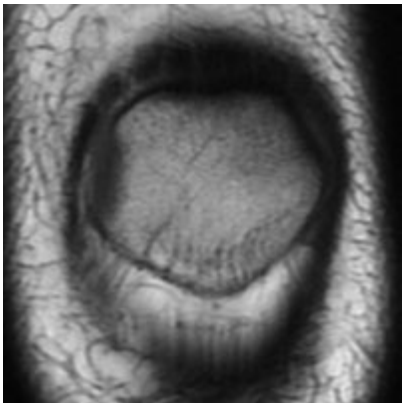
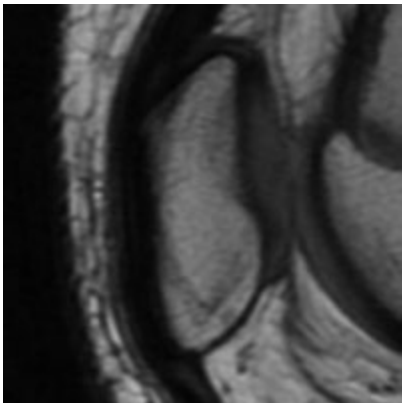
Tibia

Incomplete ossification
(Especially medially & posteriorly)
Apophysis ossified & fused

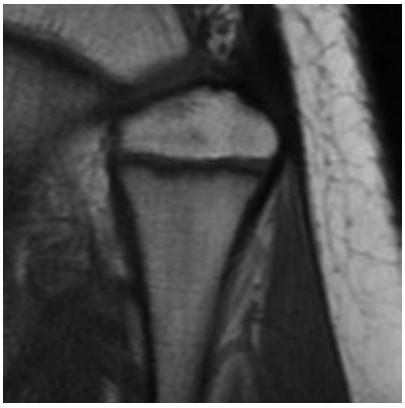
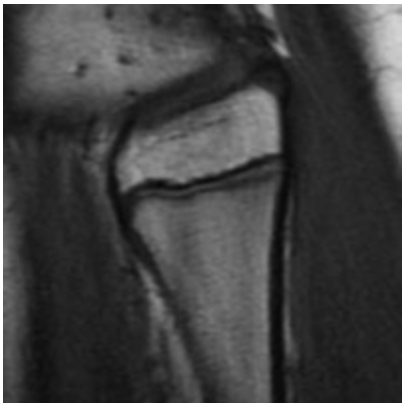
Patella

Incomplete ossification
(Especially superior tip)

Fibula

Fibular styloid not ossified

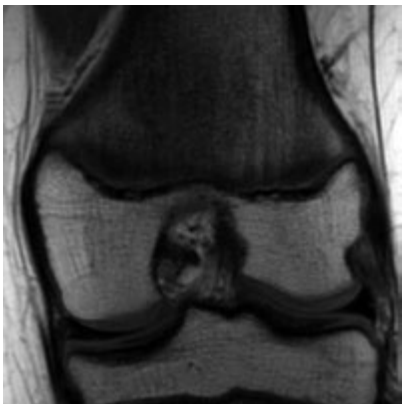



Female Standard – Age 12 Years

Coronal | Sagittal

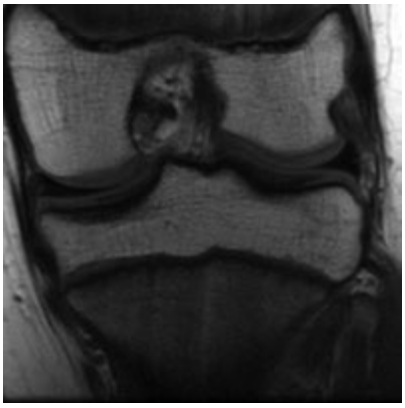
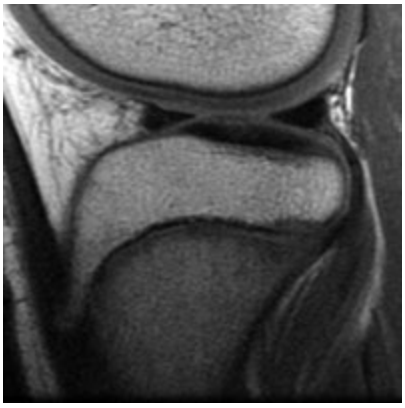
Femur

Complete ossification
Oreo sign present
Entire physis visible



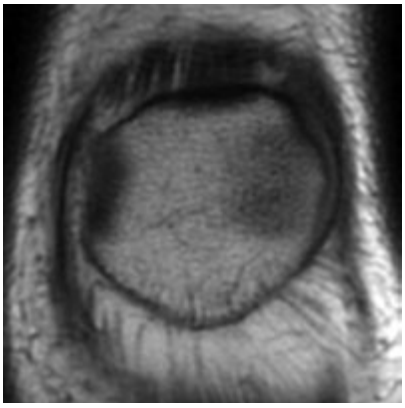
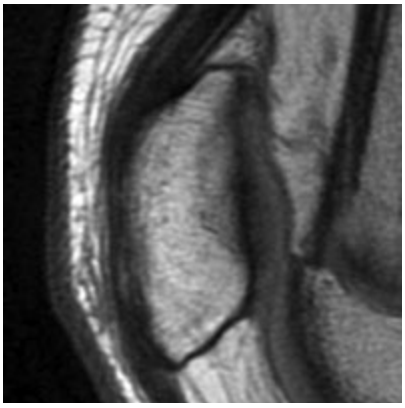

Tibia

Incomplete ossification
(especially medially & posteriorly)
Entire physis visible

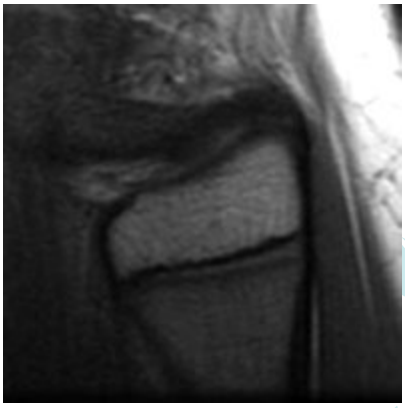
Patella

Complete ossification

Fibula

Fibular styloid not ossified
Entire physis visible

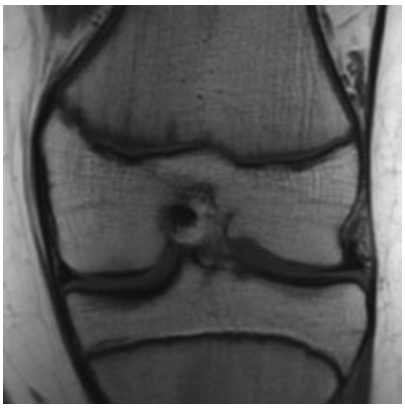
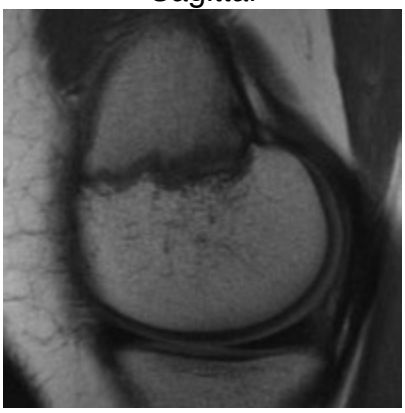



Female Standard – Age 13 Years

Coronal | Sagittal

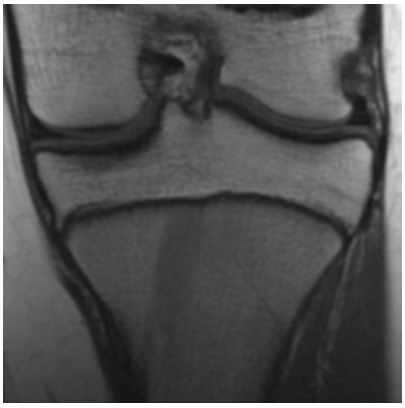
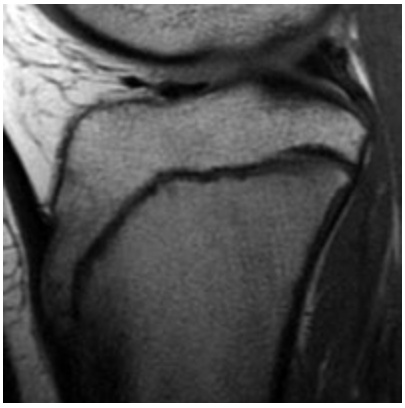
Femur

Complete ossification
Disappearance of oreo sign
Entire physis visible
Minimal physeal thinning

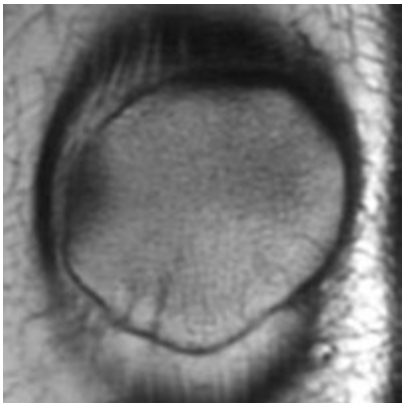
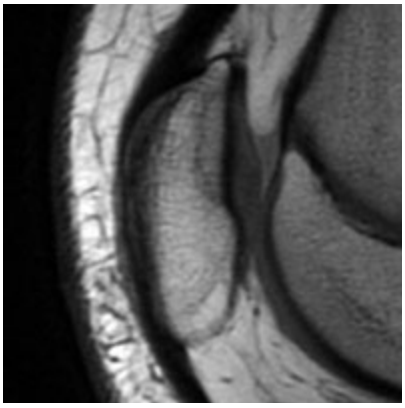
Tibia

Complete ossification
Entire physis visible
Minimal physeal thinning

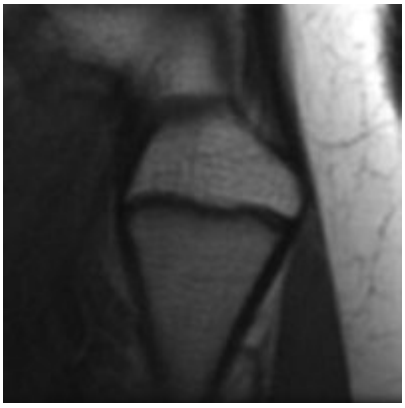
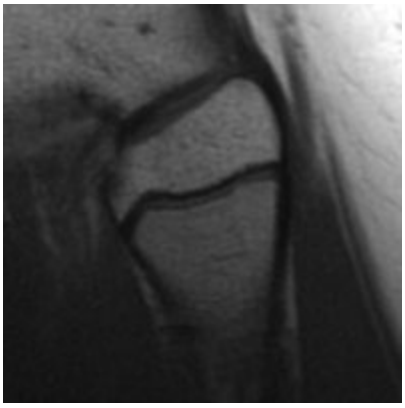
Patella

Complete ossification

Fibula

Fibular styloid not ossified
Entire physis visible
Minimal physeal thinning

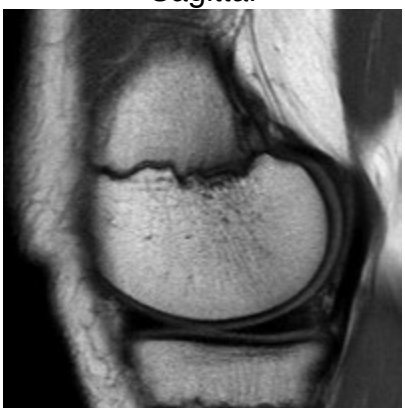



Female Standard – Age 14 Years

Coronal | Sagittal

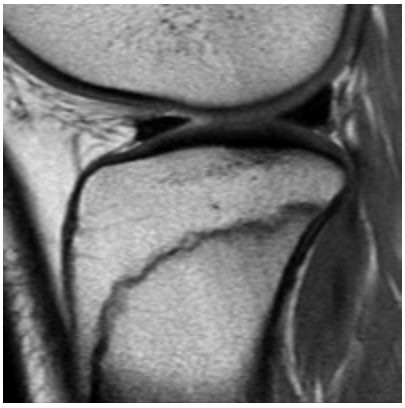
Femur

Complete ossification
Entire physis visible
Physis thinning (<2mm in height)

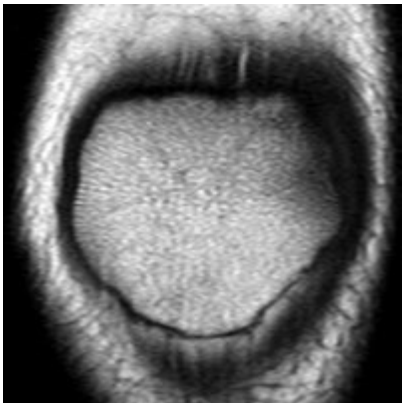
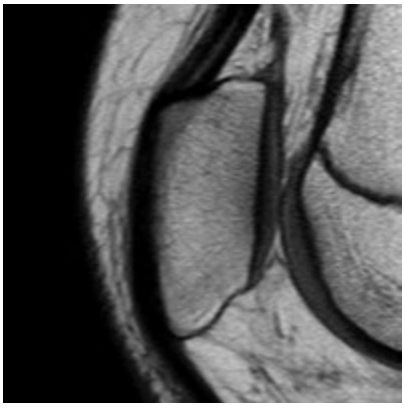
Tibia

Complete ossification
Entire physis visible
Physis thinning (<2mm in height)

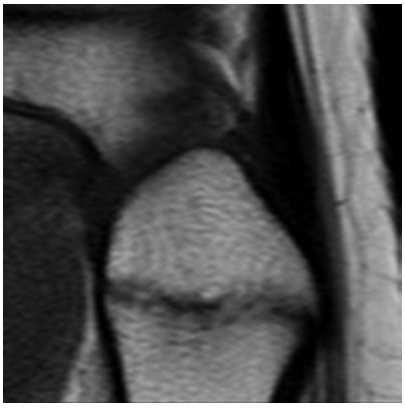
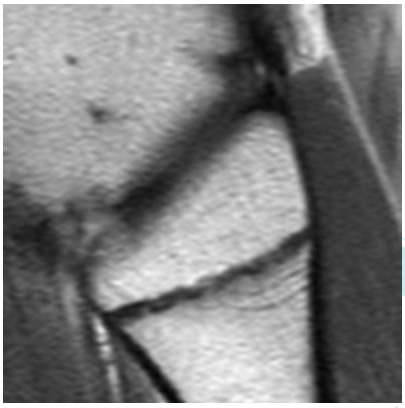
Patella

Complete ossification

Fibula

Fibular styloid ossified
Entire physis visible
Physis thinning (<2mm in height)

Female Standard – Age 15 Years

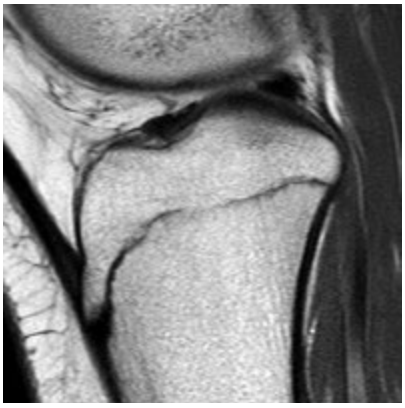
Coronal | Sagittal

Femur

Complete ossification
Entire physis visible
Physis thinning (<2mm in height)

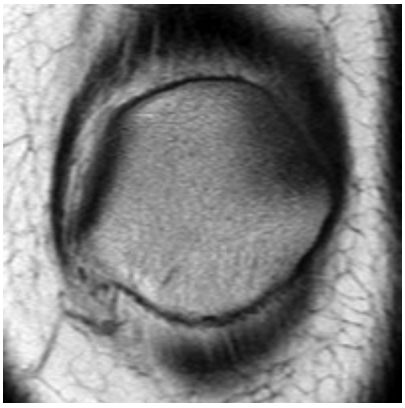
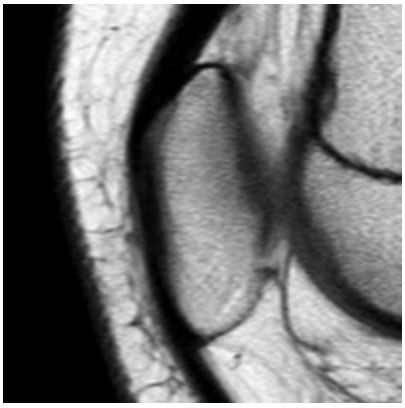

Tibia

Complete ossification
Partial closure of physis

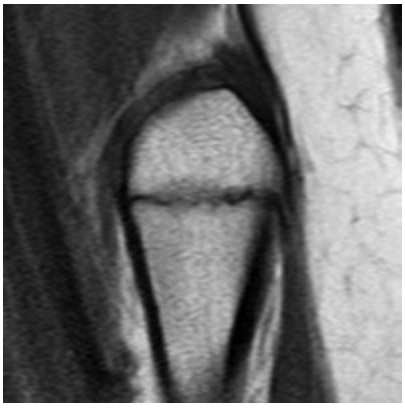
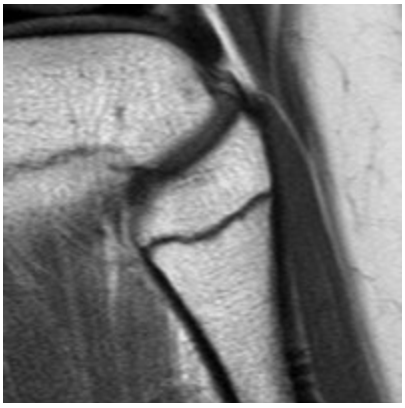
Patella

Complete ossification

Fibula

Fibular styloid ossified
Partial closure of physis
or
Entire physis visible
Physis thinning (<2mm in height)

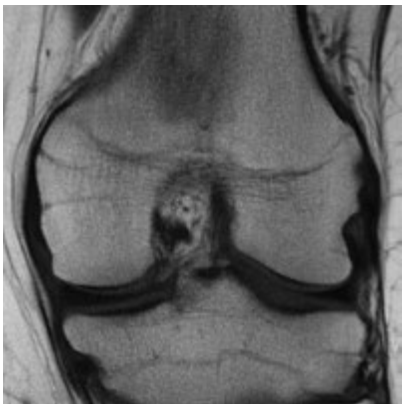
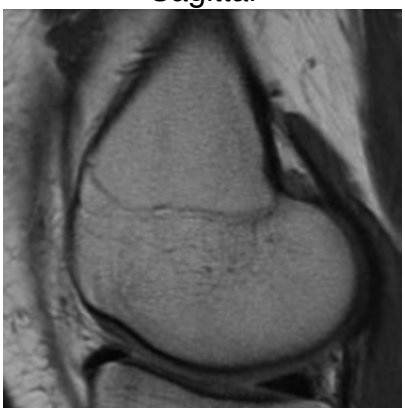



Female Standard – Age 16 Years

Coronal | Sagittal

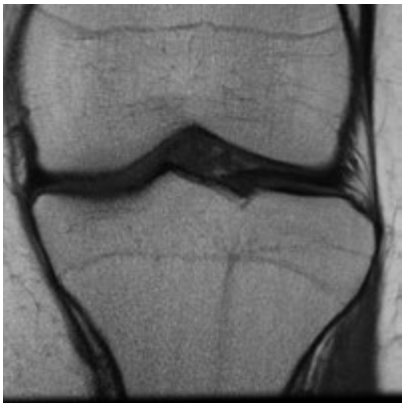
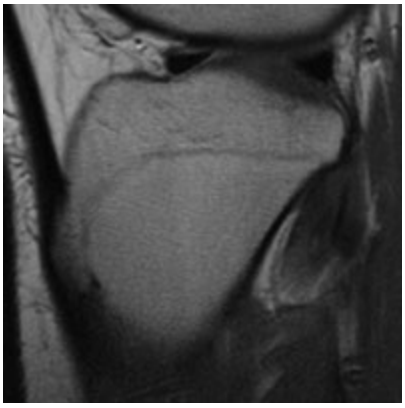
Femur

Complete ossification
Partial closure of physis

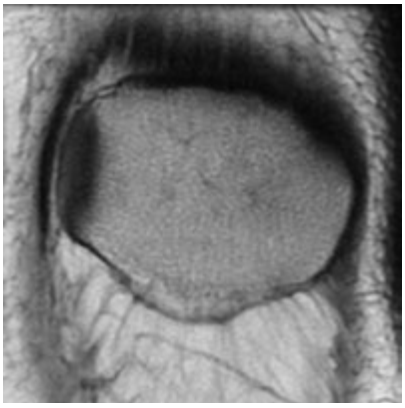
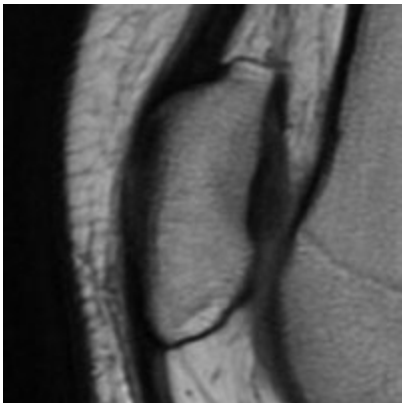
Tibia

Complete ossification
Partial or complete closure of physis

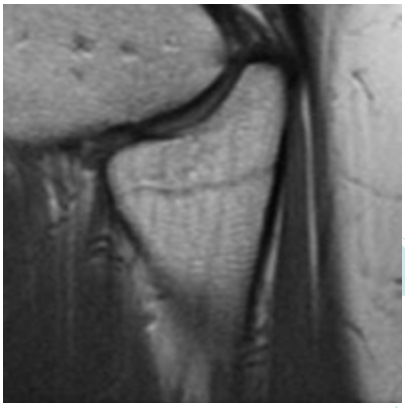
Patella

Complete ossification

Fibula

Complete ossification
Partial or complete closure of physis

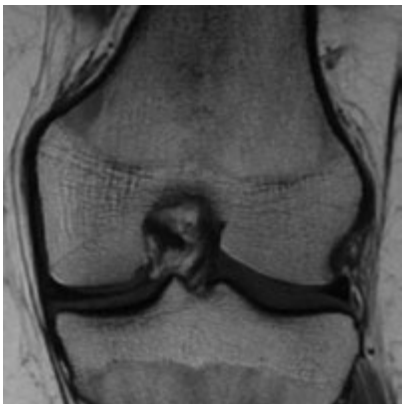
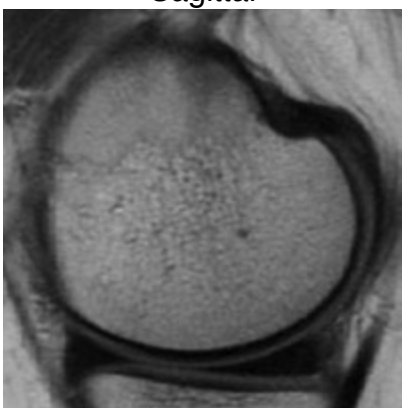



Female Standard – Age 17 Years

Coronal | Sagittal

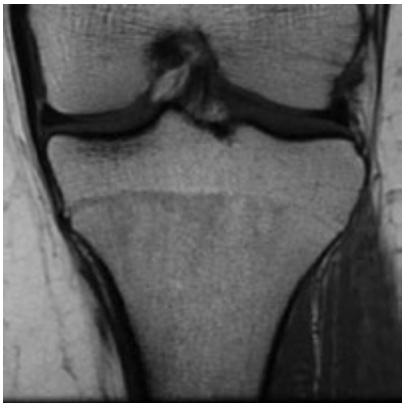
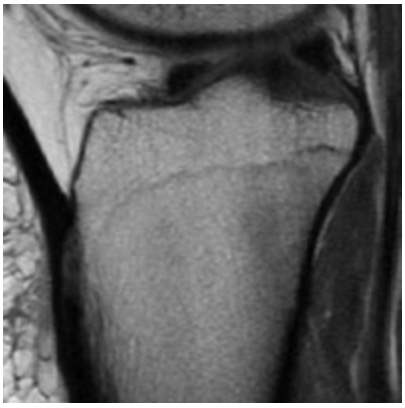
Femur

Complete ossification
Complete closure of physis

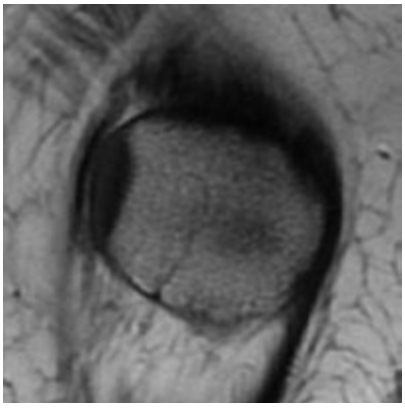
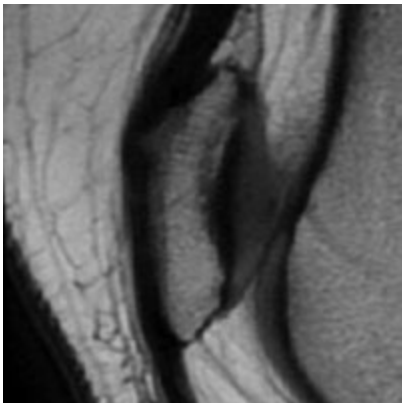
Tibia

Complete ossification
Complete closure of physis

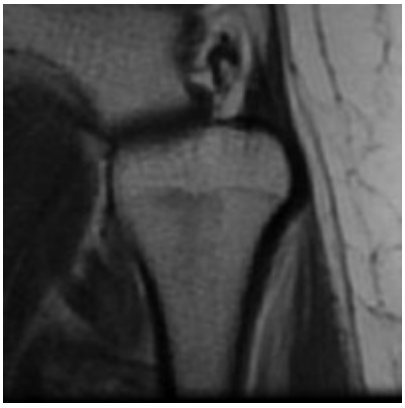
Patella

Complete ossification

Fibula

Complete ossification
Complete closure of physis

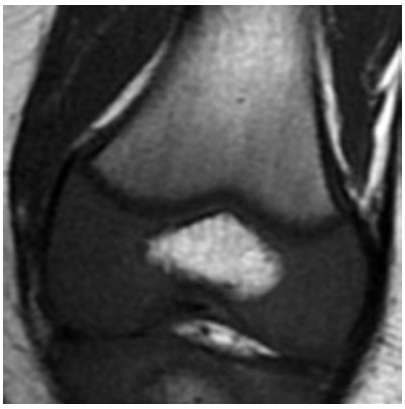
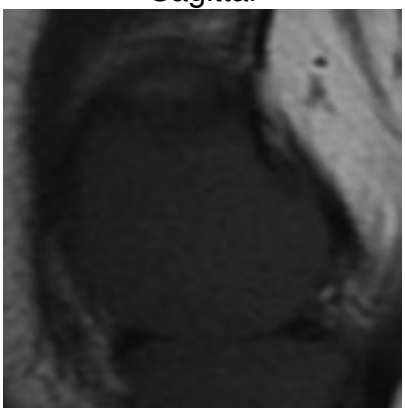



Male Standard – Age 1 Year

Coronal | Sagittal

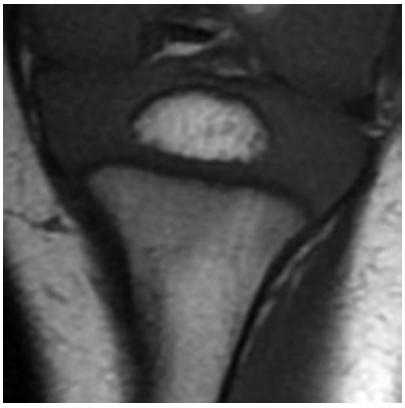
Femur

Incomplete ossification
(50-75%)
No ossification visible through the center of the medial femoral condyle on the sagittal view

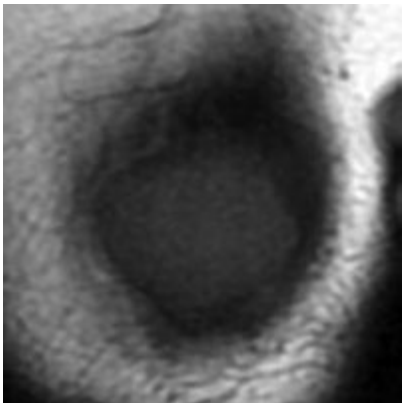
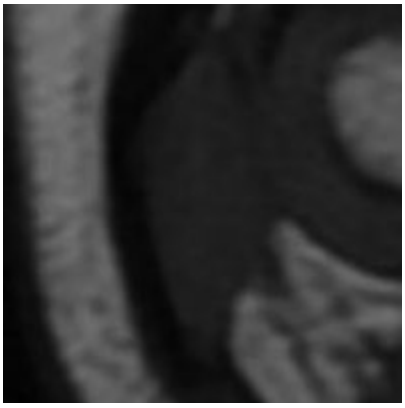
Tibia

Incomplete ossification
(25-50%)



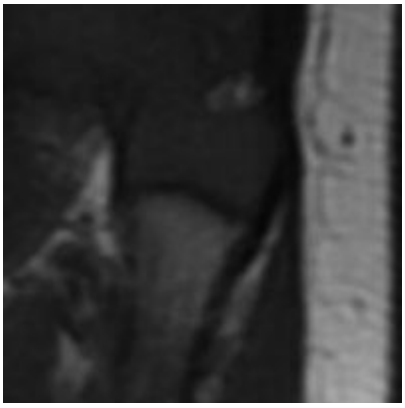
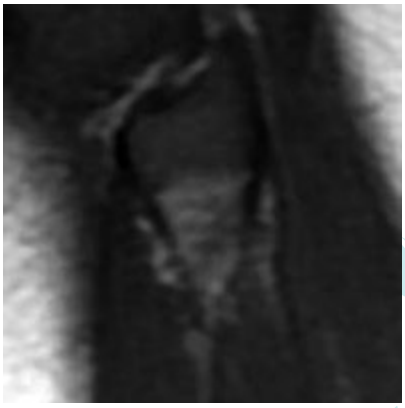

Patella

No ossification

Fibula

No epiphyseal ossification

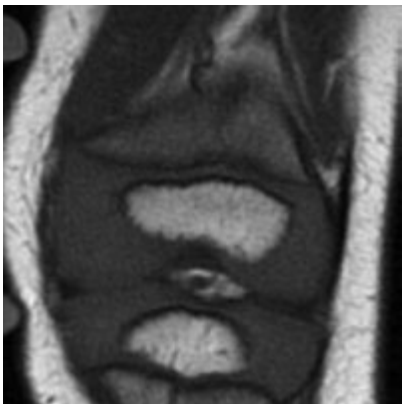
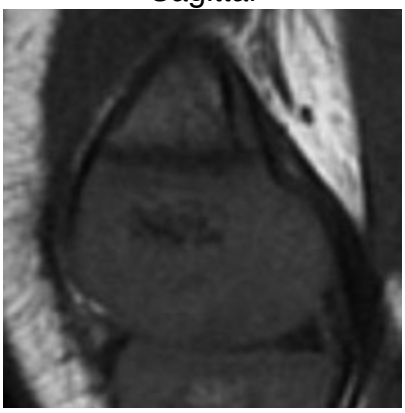



Male Standard – Age 2 Years

Coronal | Sagittal

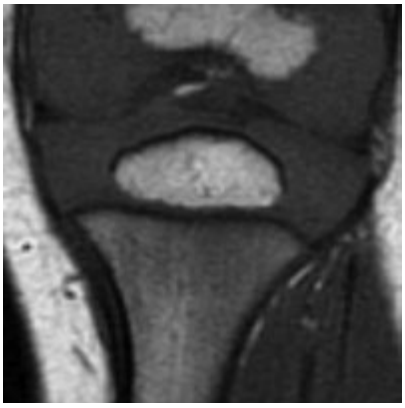
Femur

Incomplete ossification
(50-75%)
Ossification present through the center of the medial femoral condyle on the sagittal view

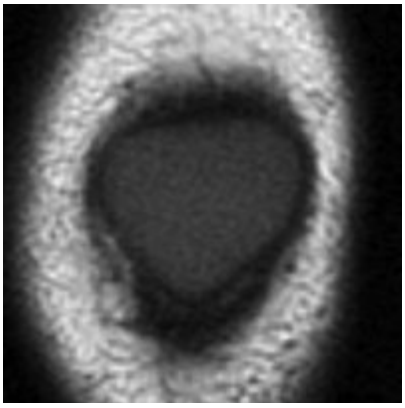
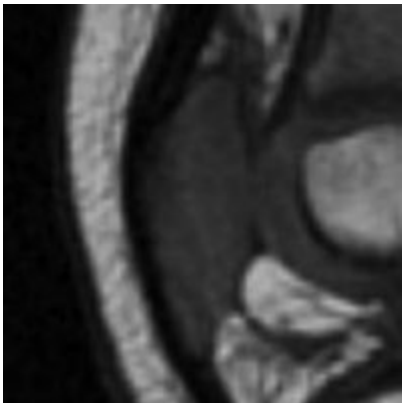
Tibia

Incomplete ossification
(50-75%)



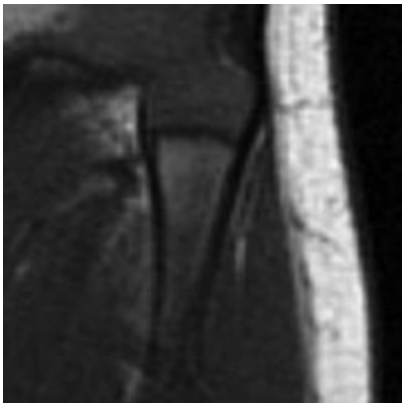
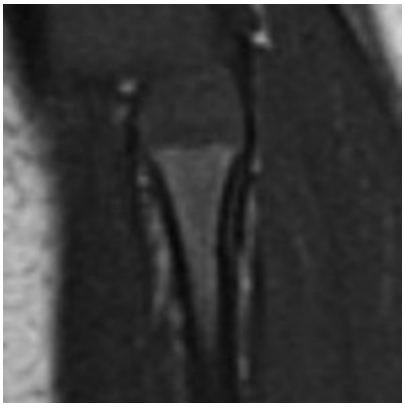

Patella

No ossification

Fibula

No epiphyseal ossification

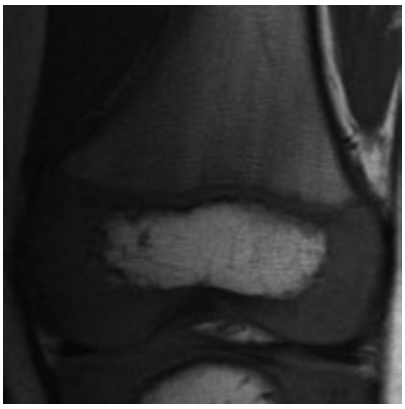



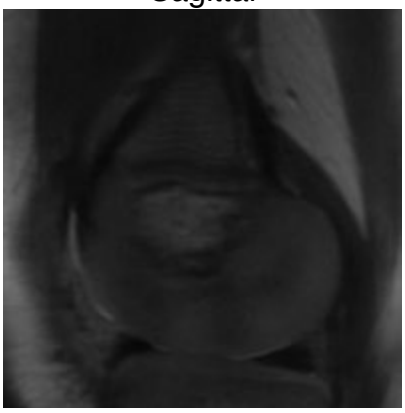
Male Standard – Age 3 Years

Coronal | Sagittal

Femur

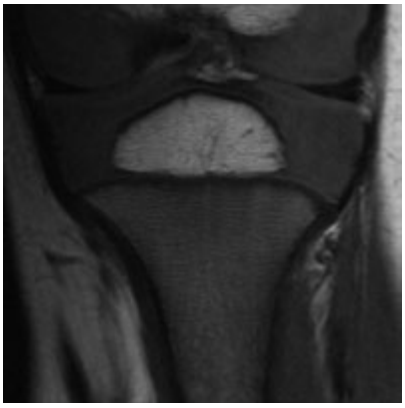
Incomplete ossification
(50-75%)





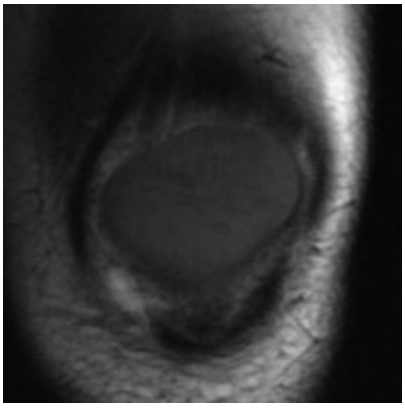
Tibia

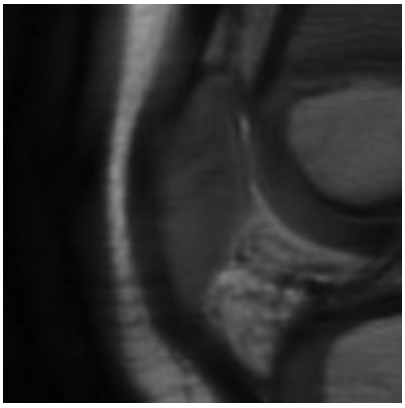
Incomplete ossification
(50-75%)



Patella

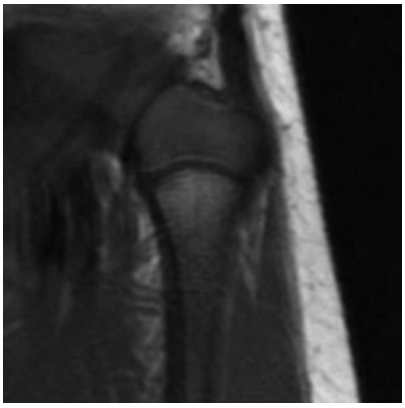
No ossification

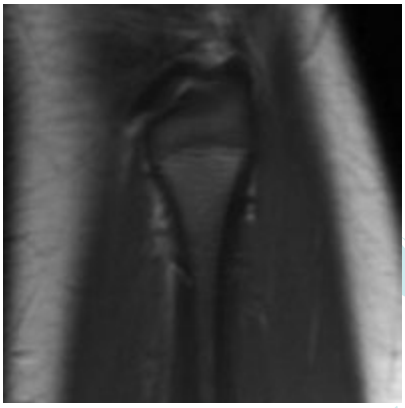




Fibula

No epiphyseal ossification



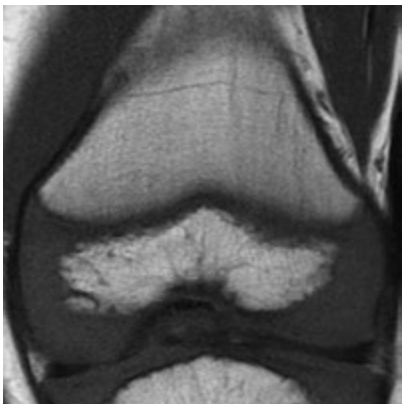
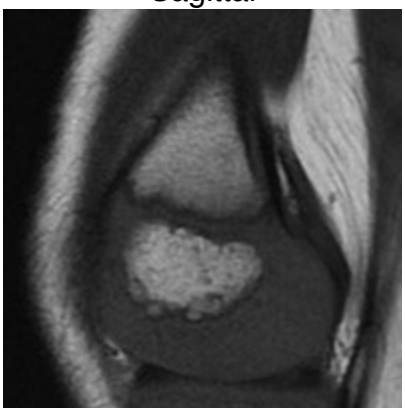


Male Standard – Age 4 Years

Coronal | Sagittal

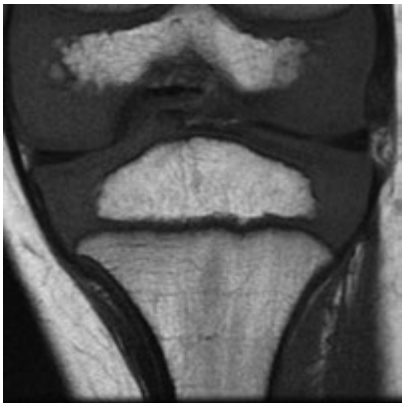
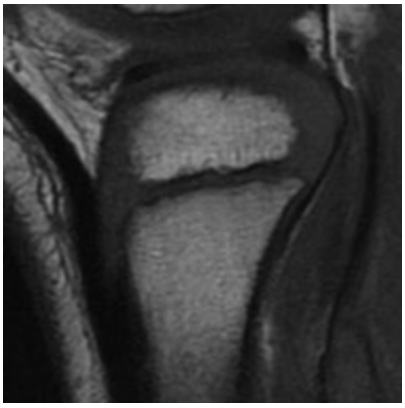
Femur

Incomplete ossification
(75-90%)

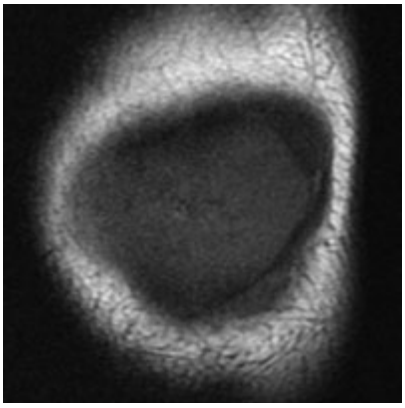
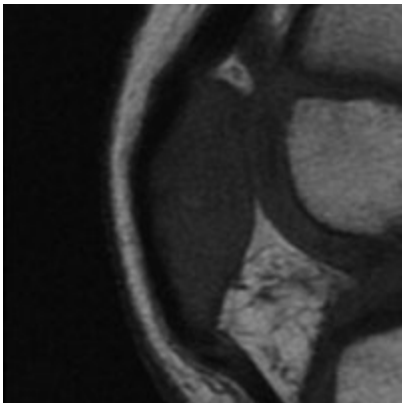
Tibia

Incomplete ossification
(50-75%)

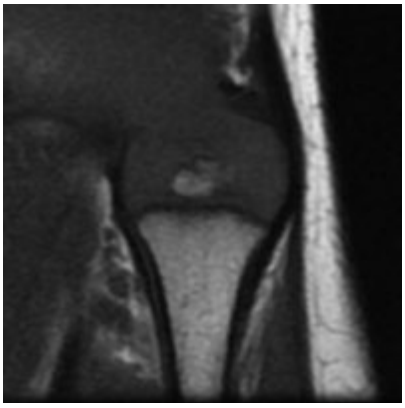
Patella

Incomplete ossification
(0-25%)

Fibula

Incomplete ossification
(<50%)

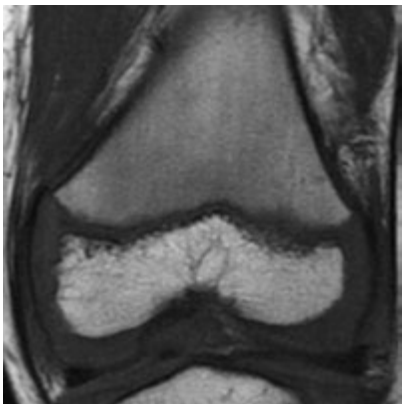



Male Standard – Age 5 Years

Coronal | Sagittal

Femur

Incomplete ossification
(75-90%)

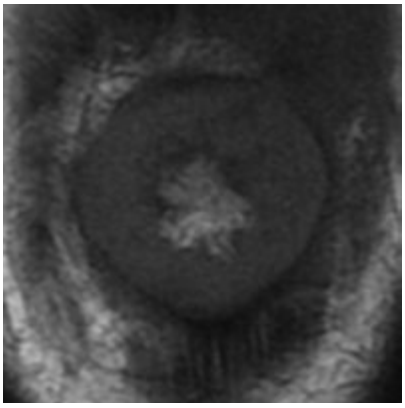
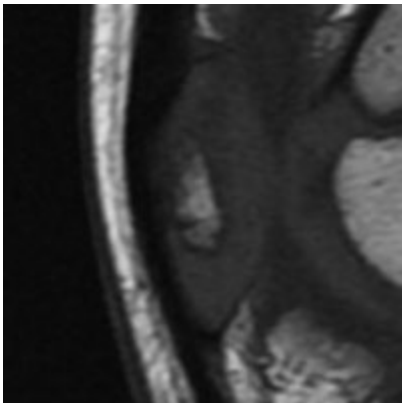



Tibia

Incomplete ossification
(50-75%)

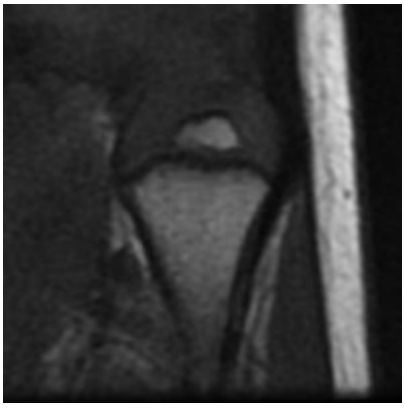
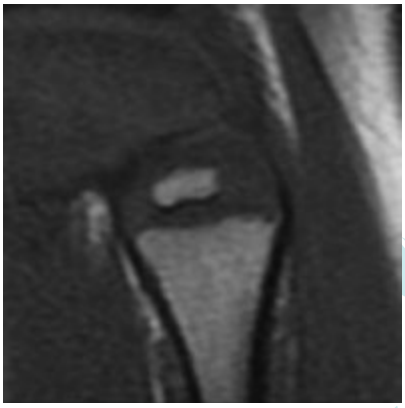

Patella

Incomplete ossification
(25-50%)

Fibula

Incomplete ossification
(25-75%)

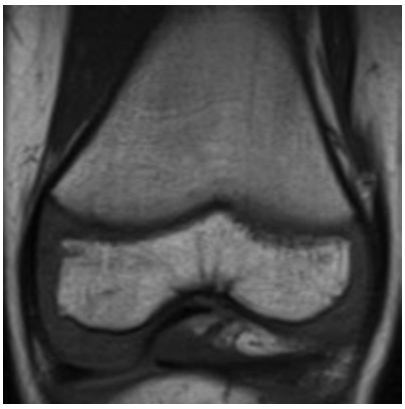



Male Standard – Age 6 Years

Coronal | Sagittal

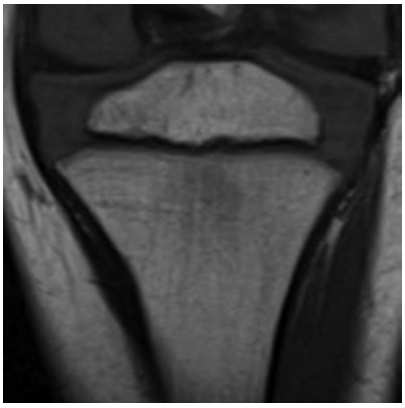
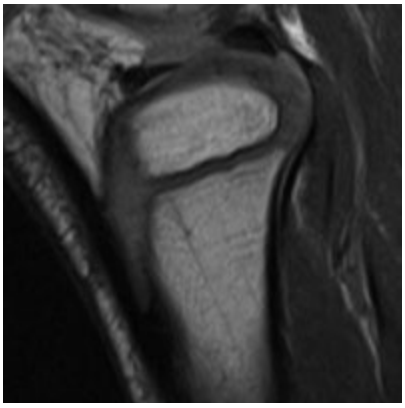
Femur

Incomplete ossification
(75-90%)



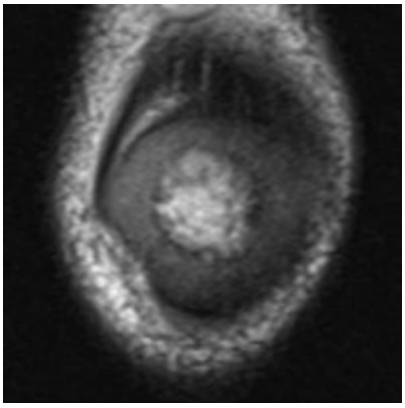
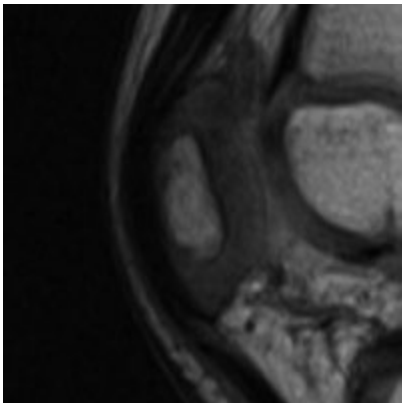

Tibia

Incomplete ossification
(50-75%)

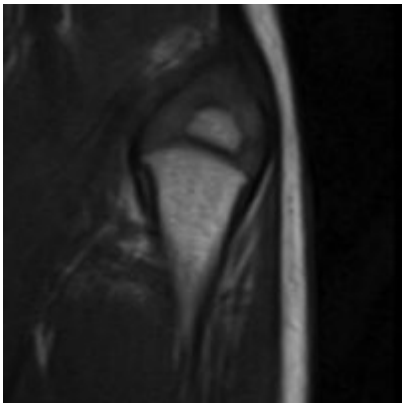
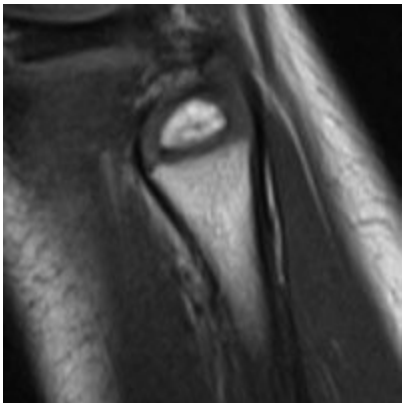
Patella

Incomplete ossification
(33-66%)

Fibula

Incomplete ossification
(25-75%)

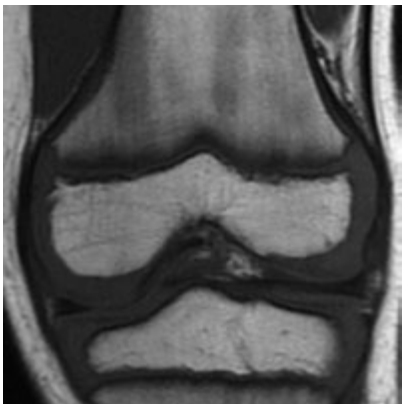
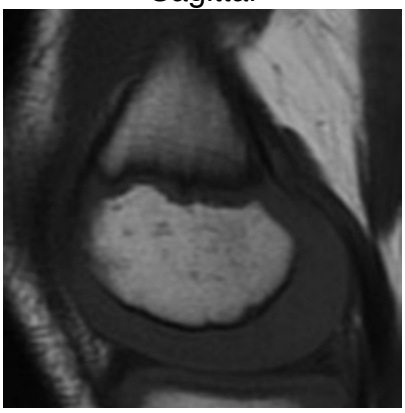



Male Standard – Age 7 Years

Coronal | Sagittal

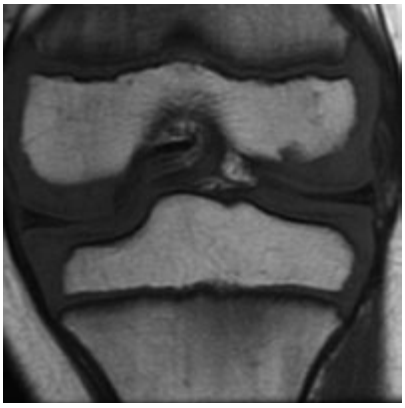
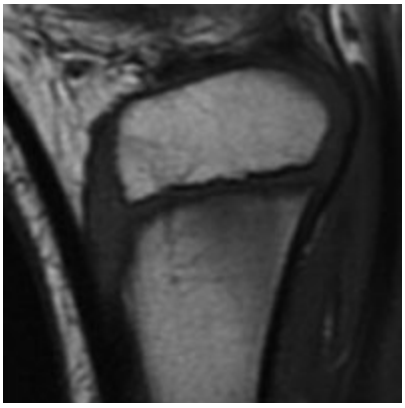
Femur

Incomplete ossification
(75-90%)

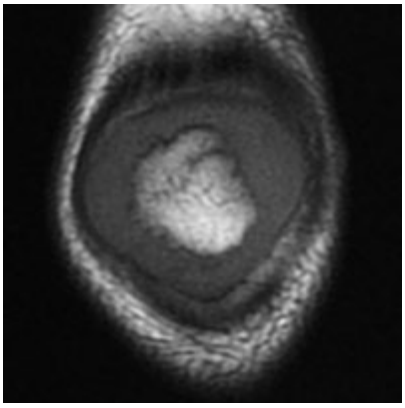
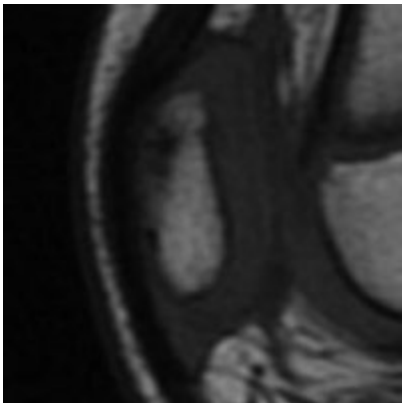
Tibia

Incomplete ossification
(75-90%)
Tibial spine “bump”

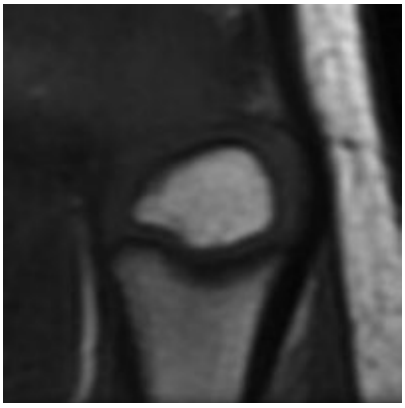
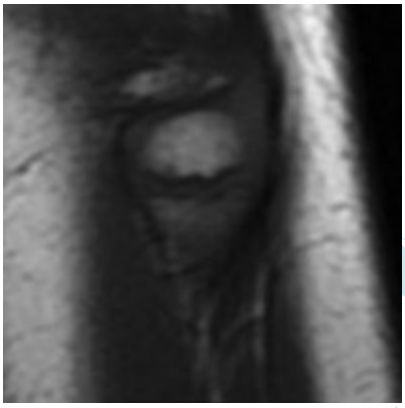
Patella

Incomplete ossification
(50-75%)

Fibula

Incomplete ossification
(50-75%)

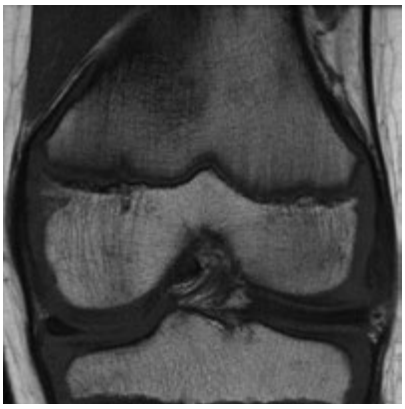
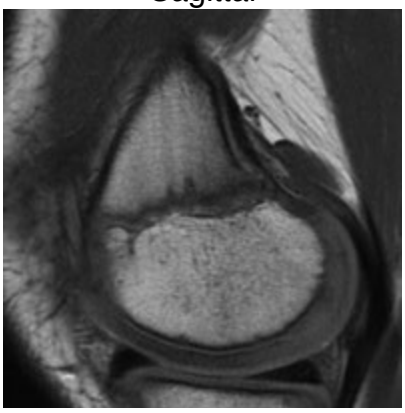



Male Standard – Age 8 Years

Coronal | Sagittal

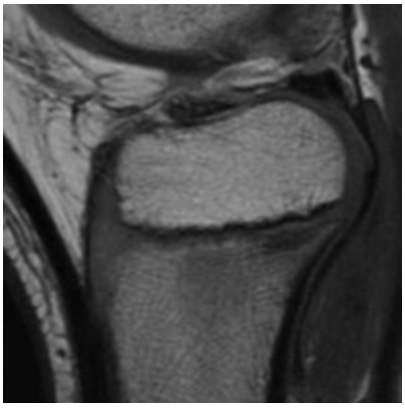
Femur

Incomplete ossification
(>90%)
Oreo sign present

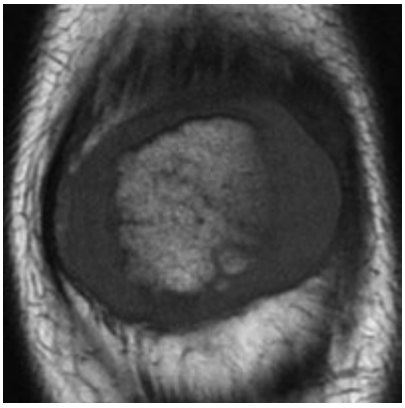
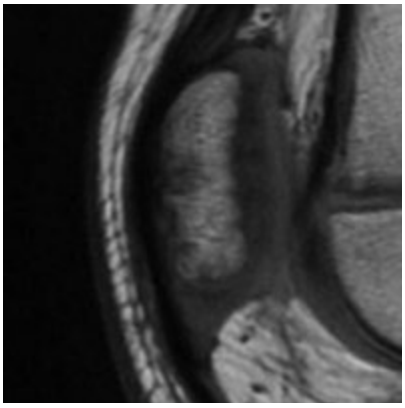
Tibia

Incomplete ossification
(75-90%)
Tibial spine “bump”

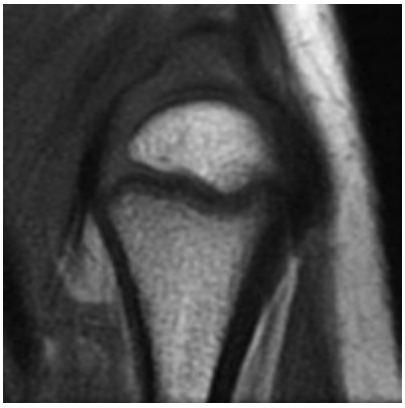
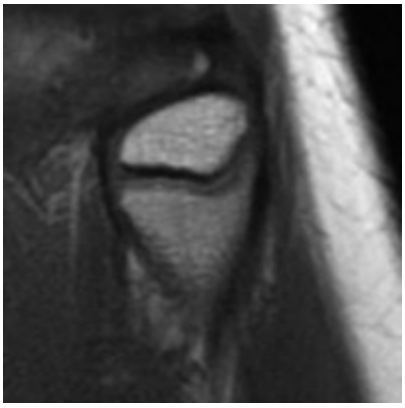
Patella

Incomplete ossification
(>75%)
(Superior and inferior tips)

Fibula

Incomplete ossification
(75-95%)

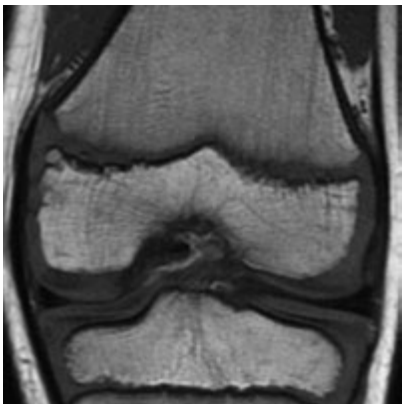
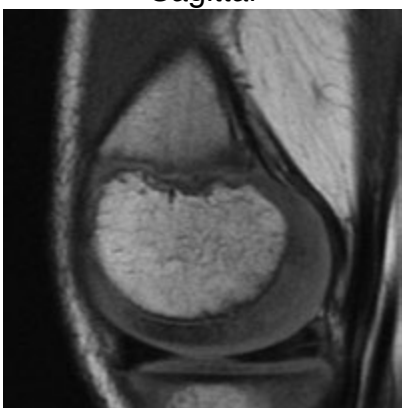



Male Standard – Age 9 Years

Coronal | Sagittal

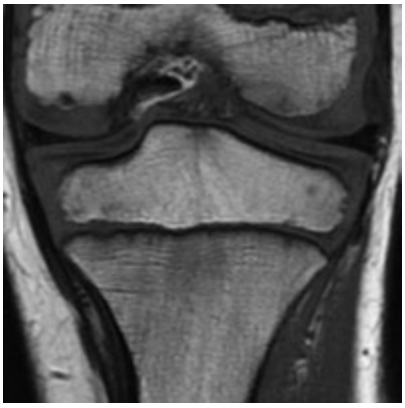
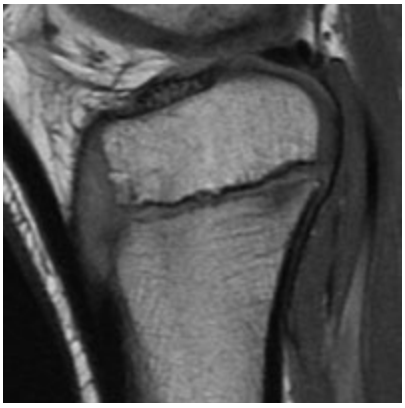
Femur

Incomplete ossification
(>90%)
Oreo sign present

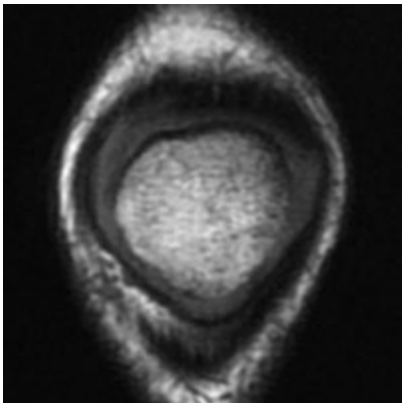
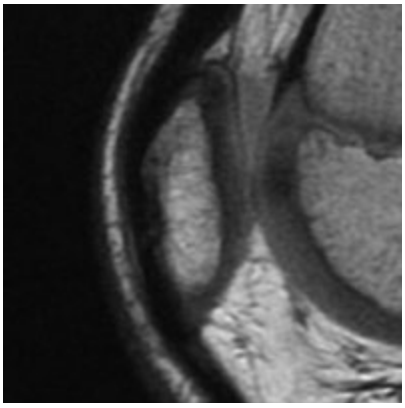
Tibia

Incomplete ossification
(75-90%)
Tibial spine “bump”

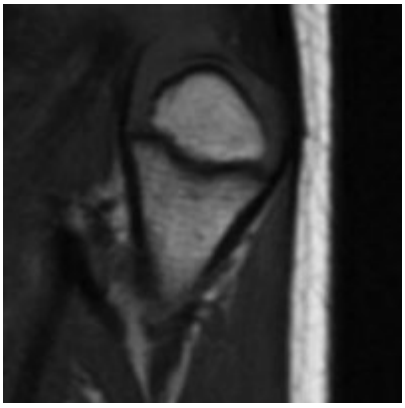
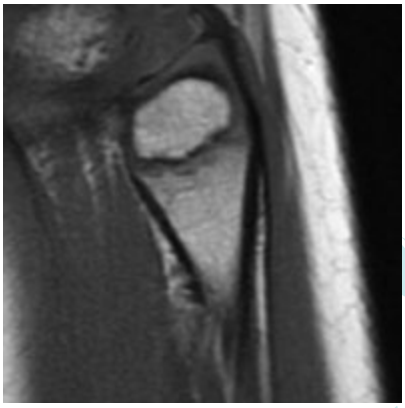
Patella

Incomplete ossification
(>75%)
(Superior and inferior tips)

Fibula

Incomplete ossification
(75-95%)

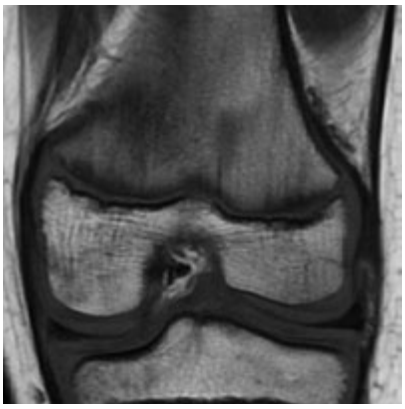
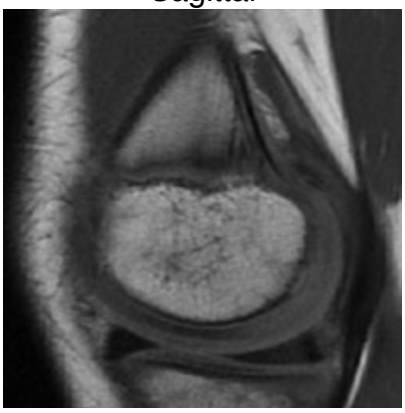



Male Standard – Age 10 Years

Coronal | Sagittal

Femur

Incomplete ossification
(>90%)
Oreo sign present

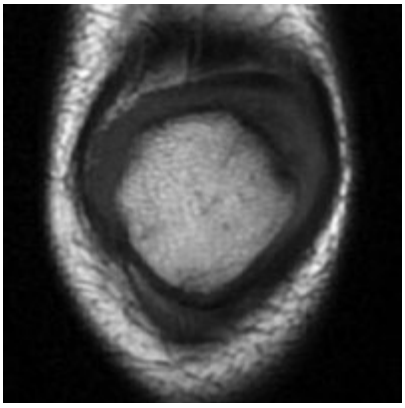
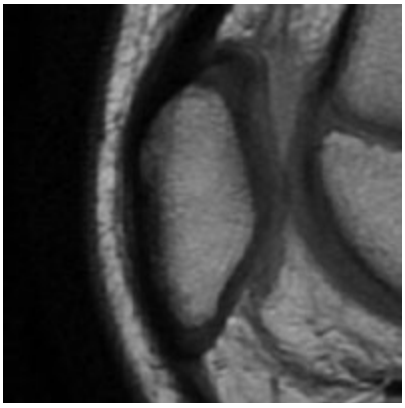



Tibia

Incomplete ossification
(>90%)
Ossified tibial spines

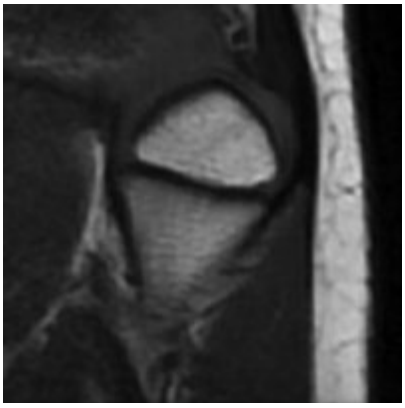
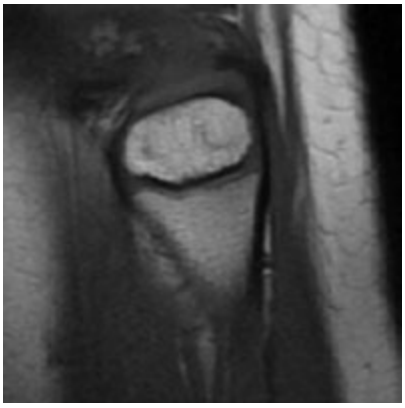

Patella

Incomplete ossification
(Superior and inferior tips)

Fibula

Incomplete ossification
Fibular styloid not ossified

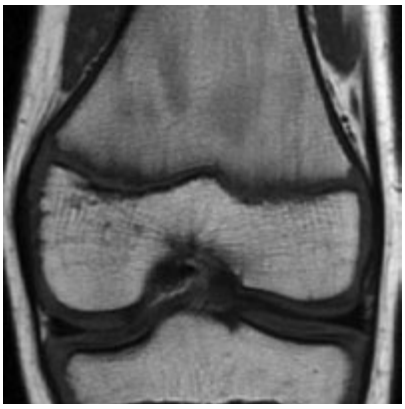
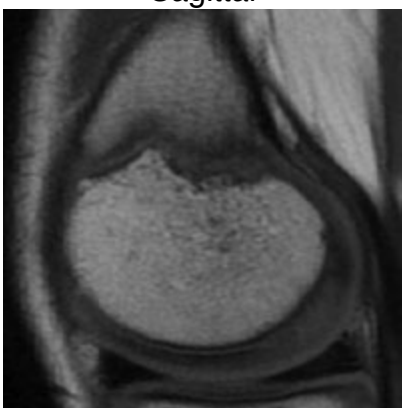



Male Standard – Age 11 Years

Coronal | Sagittal

Femur

Incomplete ossification
(>90%)
Oreo sign present

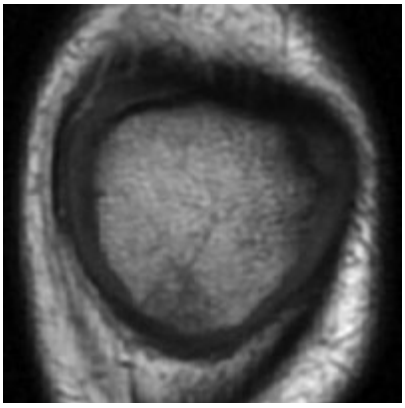
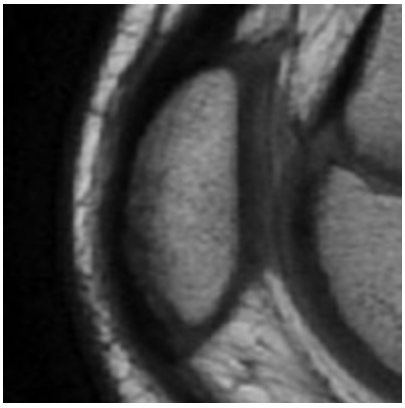



Tibia

Incomplete ossification
(Medially and laterally)
No apophyseal ossification
Tubercle epiphyseal extension

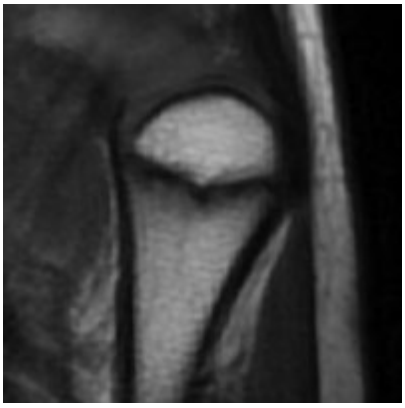
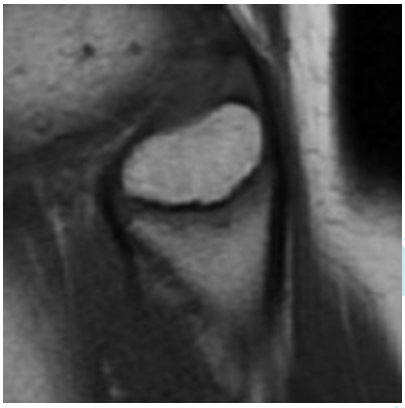

Patella

Incomplete ossification
(Superior and inferior tips)

Fibula

Incomplete ossification
Fibular styloid not ossified

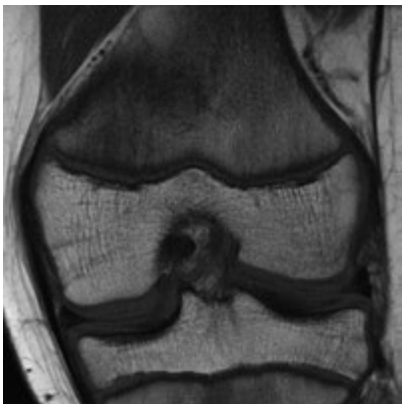



Male Standard – Age 12 Years

Coronal | Sagittal

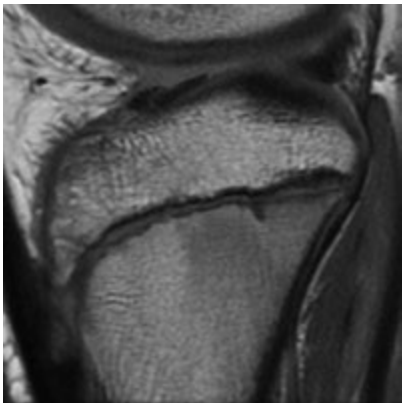
Femur

Incomplete ossification
(Especially medially)
Oreo sign present



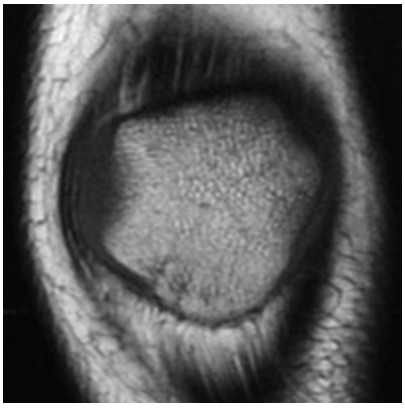
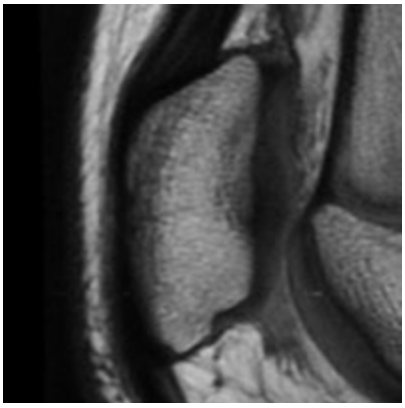

Tibia

Incomplete ossification
(Especially medially and posteriorly)
Apophysis ossification, but not fused

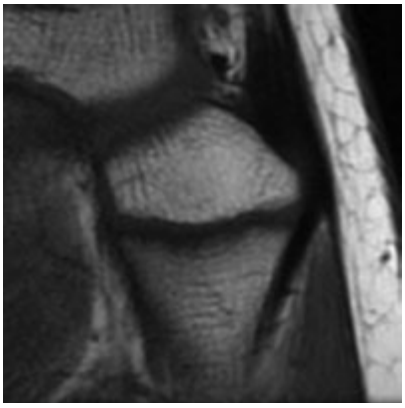
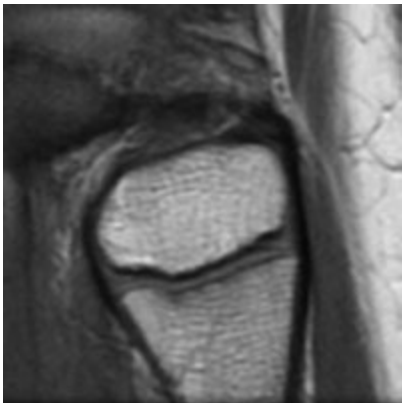
Patella

Incomplete ossification
(Superior tip)

Fibula

Incomplete ossification
Fibular styloid not ossified

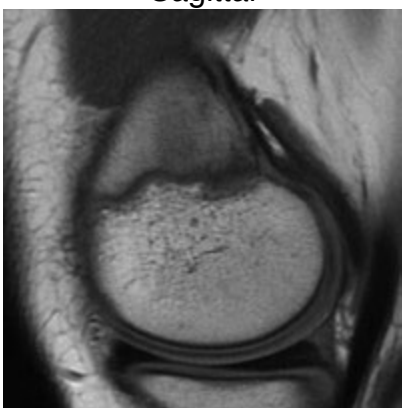



Male Standard – Age 13 Years

Coronal | Sagittal

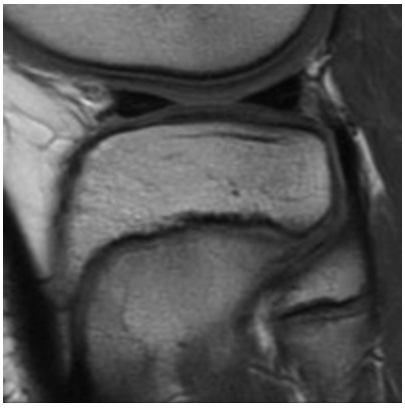
Femur

Incomplete ossification
(Especially medially)
Oreo sign present

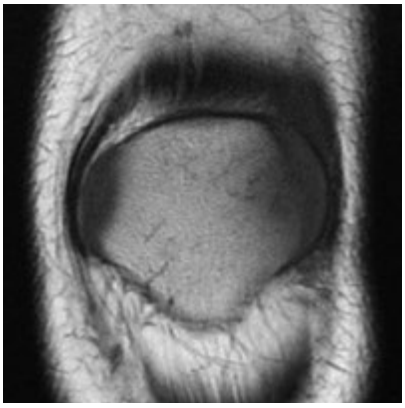
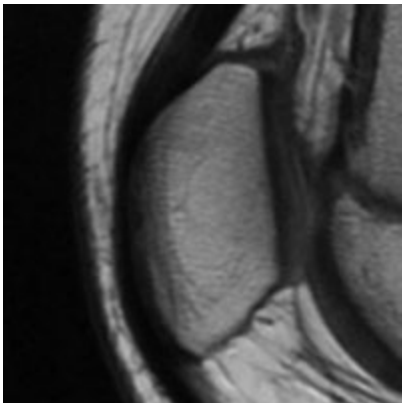
Tibia

Incomplete ossification
(Especially medially and posteriorly)
Apophysis ossification and fusing “crack”

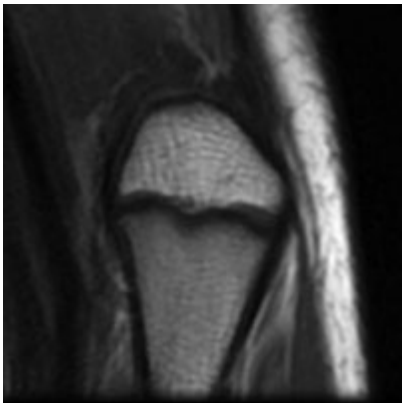
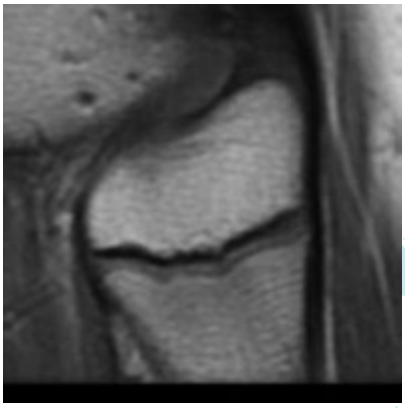
Patella

Incomplete ossification
(Especially superior tip)

Fibula

Fibular styloid not ossified

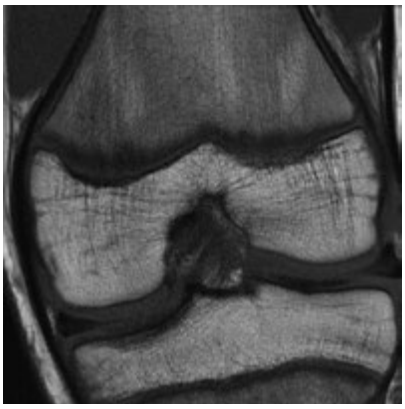
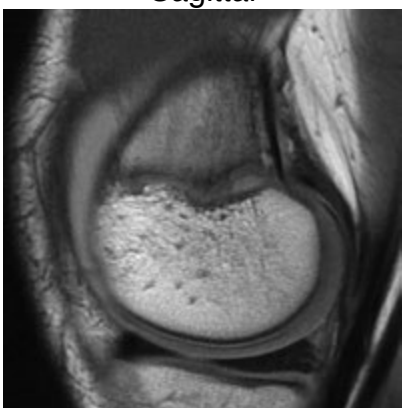



Male Standard – Age 14 Years

Coronal | Sagittal

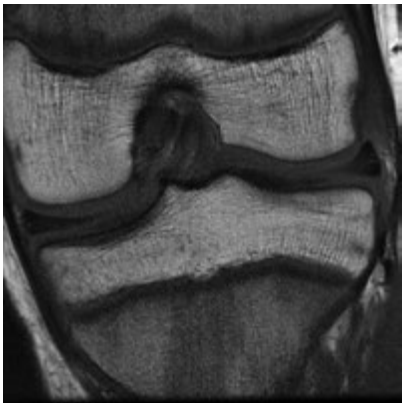
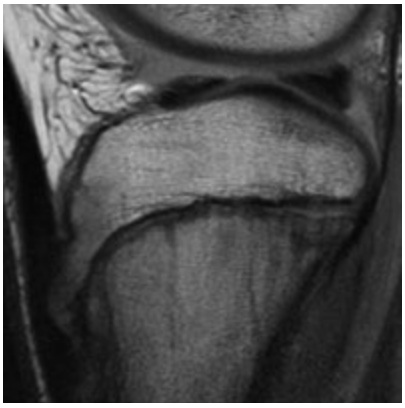
Femur

Complete ossification
Oreo sign present

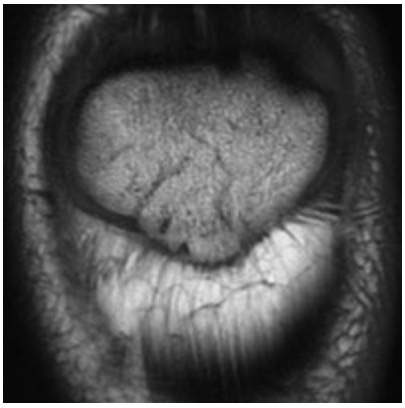
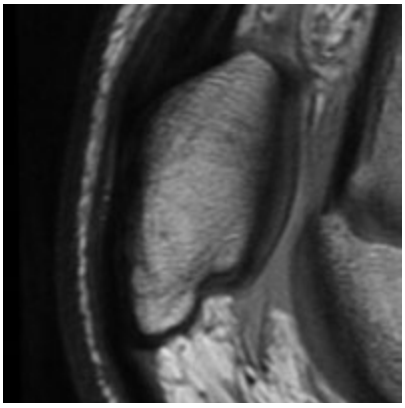
Tibia

Incomplete ossification
(Especially medially and posteriorly)
Apophysis ossification and fused

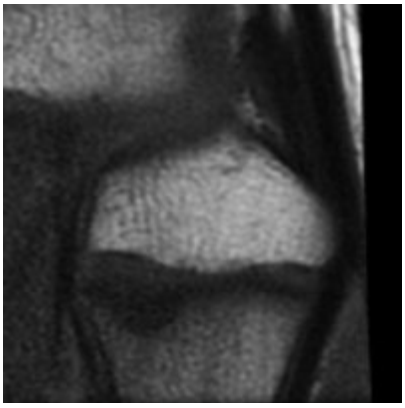
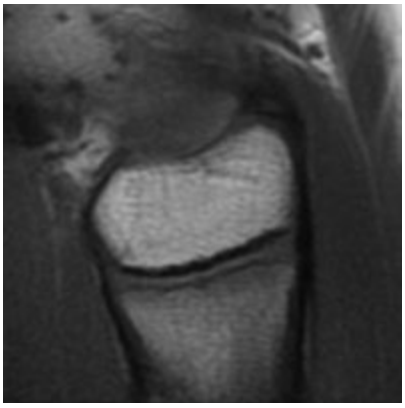
Patella

Incomplete ossification
(Especially superior tip)

Fibula

Fibular styloid not ossified

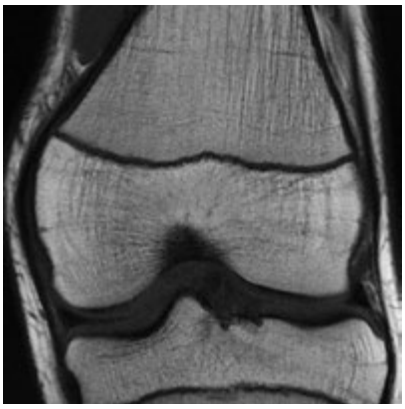



Male Standard – Age 15 Years

Coronal | Sagittal

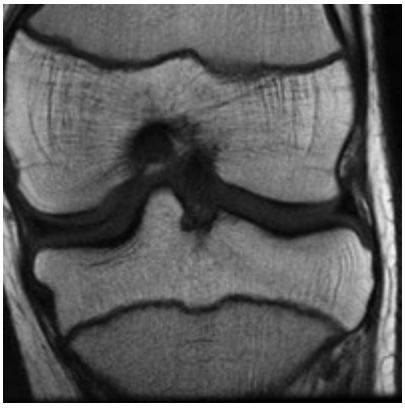
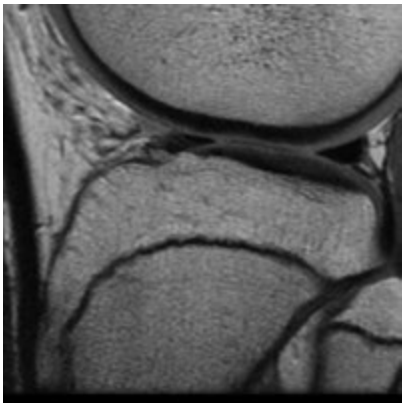
Femur

Complete ossification
Disappearance of oreo sign
Entire physis visible



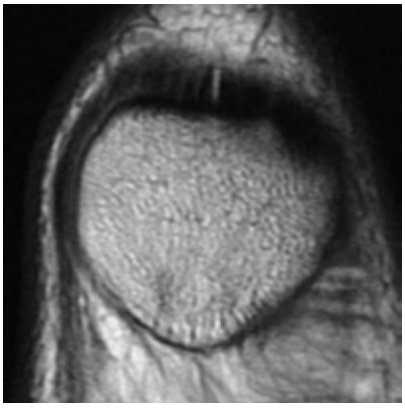
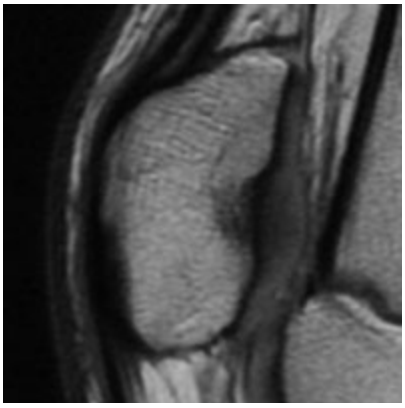

Tibia

Incomplete ossification
(Especially medially and posteriorly)
Entire physis visible

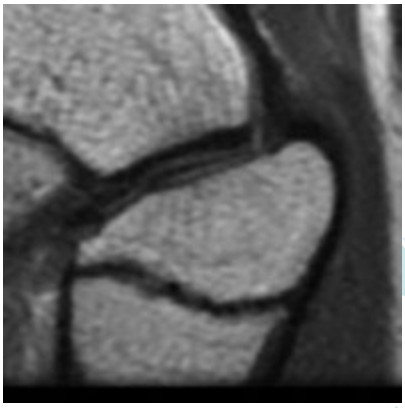
Patella

Complete ossification

Fibula

Fibular styloid not ossified
Entire physis visible

Male Standard – Age 16 Years

Coronal | Sagittal

Femur

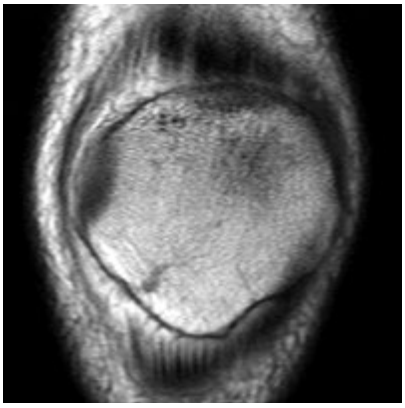
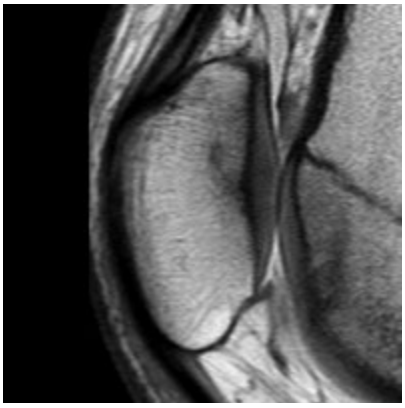
Complete ossification
Entire physis visible
Physis thinning (<2mm in height)


Tibia

Complete ossification
Partial closure of physis


Patella

Complete ossification

Fibula

Fibular styloid ossified
Physis thinning (<2mm in height)
or
Partial closure of physis


Male Standard – Age 17 Years

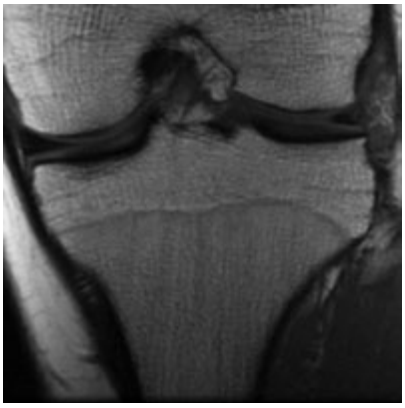
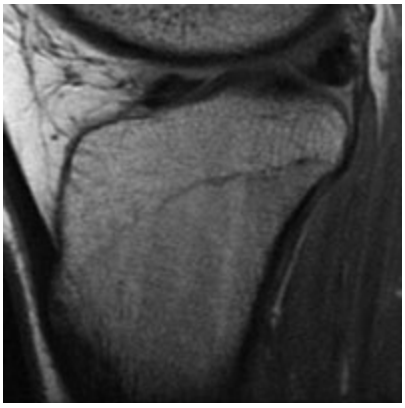
Coronal | Sagittal

Femur

Complete ossification
Partial closure of physis

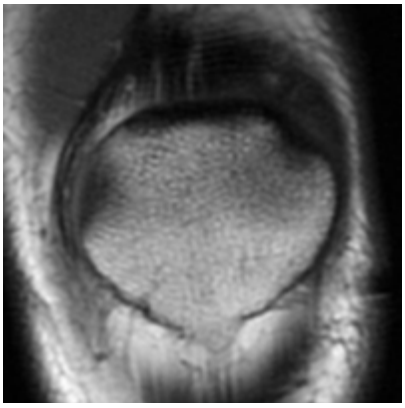
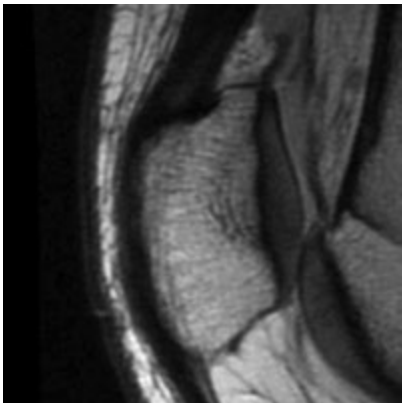

Tibia

Complete ossification
Partial or complete closure of physis

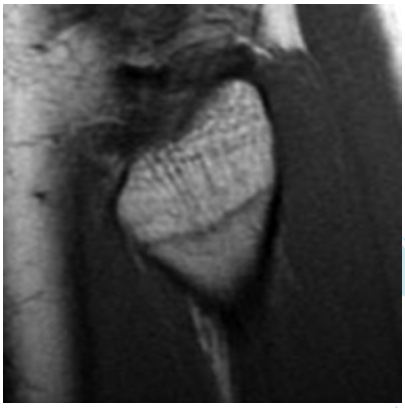
Patella

Complete ossification

Fibula

Complete ossification
Partial or complete closure of physis

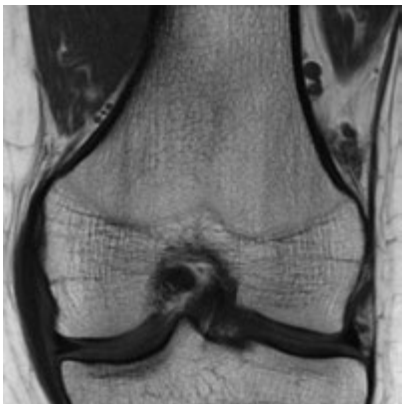
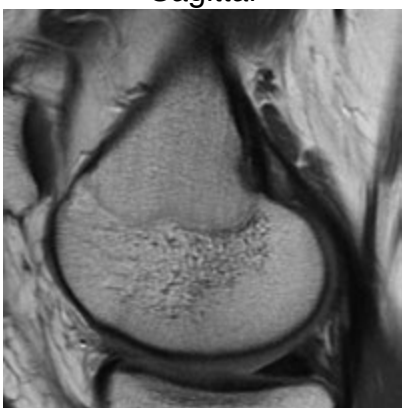



Male Standard – Age 18 Years

Coronal | Sagittal

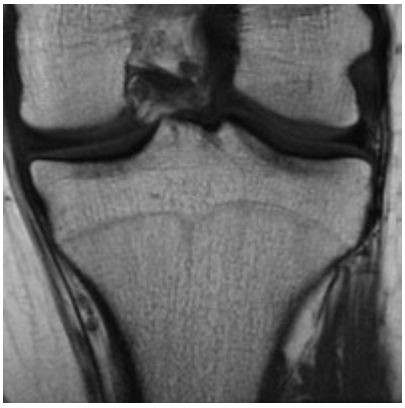
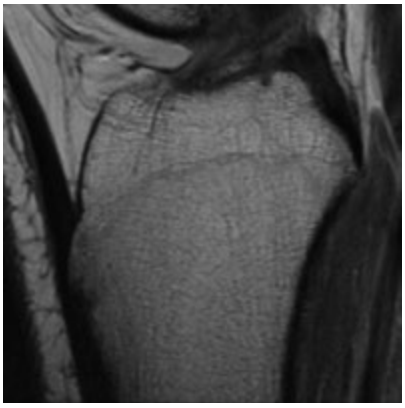
Femur

Complete ossification
Complete closure of physis

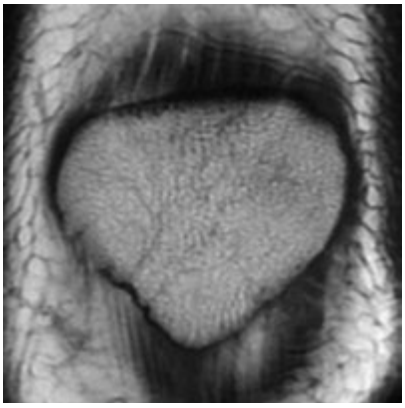
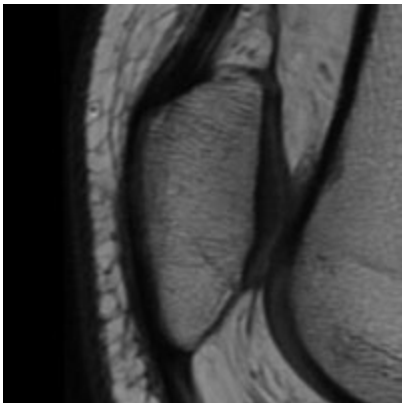
Tibia

Complete ossification
Complete closure of physis

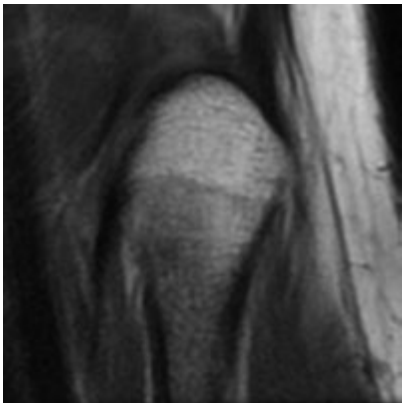
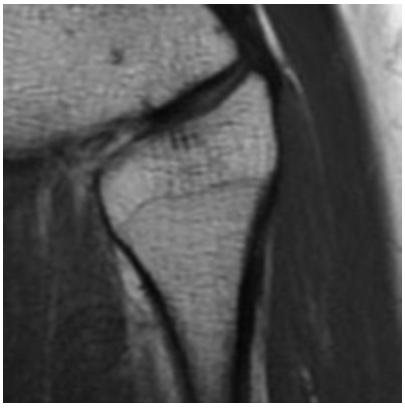
Patella

Complete ossification

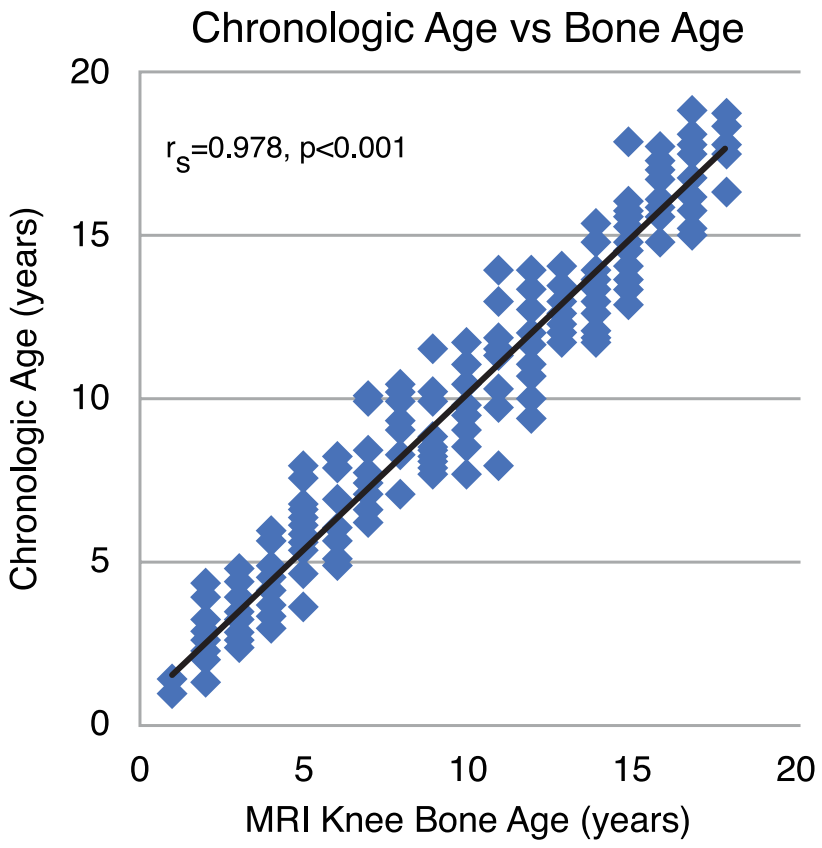



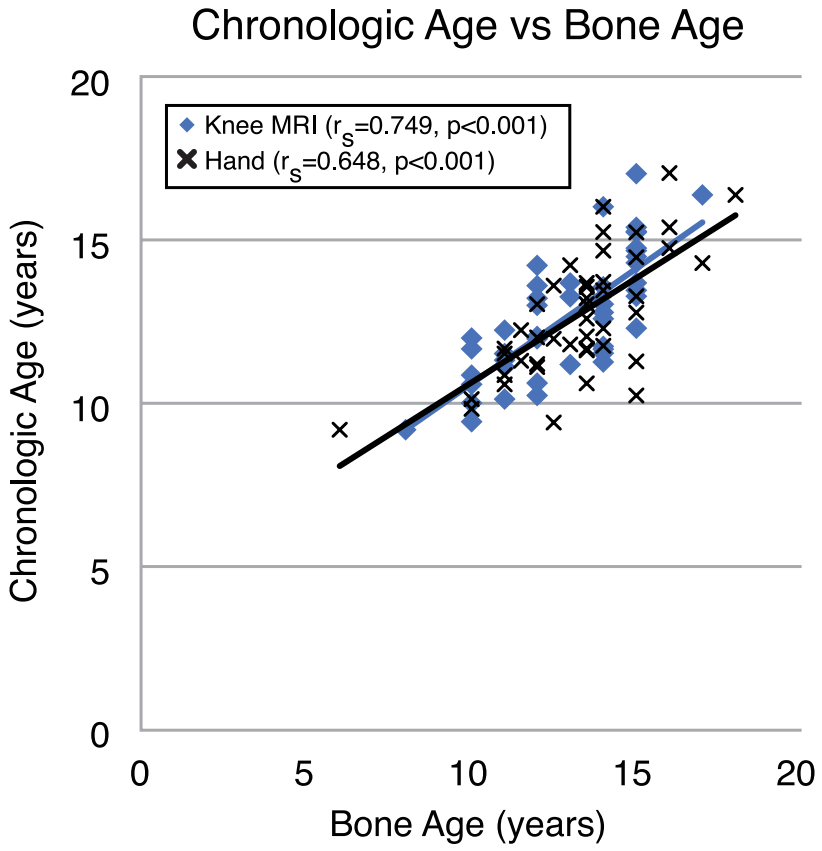
Fibula

Complete ossification
Complete closure of physis

Validation





This system of assessing bone age was validated using a cohort of 323 knee MRIs. These were separate from the knee MRIs used to create the system. Two orthopedic surgeons were blinded to this cohort of subject's chronological ages while they determined bone age using this new system.

Inter-observer reliability between the two surgeons was assessed using the intraclass correlation coefficient (ICC). Inter-observer reliability among our two surgeons was found to be high with an ICC of 0.957, p<0.001.

The comparison of knee MRI bone ages to chronological bone age was found to be highly correlated, with Spearman's rho being 0.978, p<0.001.

Left hand x-rays were available on 48 of the patients in the cohort used to validate this system. The Greulich and Pyle atlas was used to determine bone age from the wrist x-rays in this cohort. The graph to the left shows that the Greulich and Pyle bone age method and the knee MRI bone age method were similarly correlated to chronological age, with the knee MRI method having a marginally higher correlation with chronological age.

Pennock A.T., Bomar J.D., Manning J.D.: The Creation and Validation of a Knee Bone Age Atlas Utilizing MRI. J Bone Joint Surg Am. 2018;100(4):e20.

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